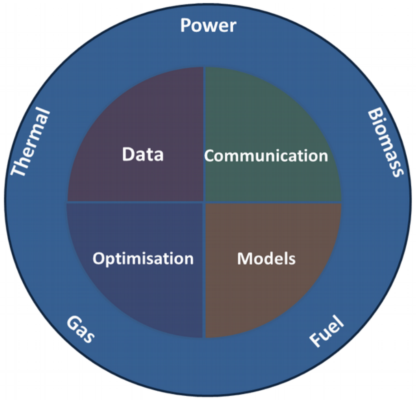
How to Accelerate the Transition to a Fossil-free Society Using Smart Buildings



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Quote by B. Obama at the Climate Summit 2014
in New York:

We are the ***first generation*** *affected by climate changes,*

and we are the ***last generation*** *able to do something about it!*

Potentials and Challenges for renewable energy

- **Scenario**: We want to cover the worlds entire need for power using wind power.
- How large an area should be covered by wind turbines?

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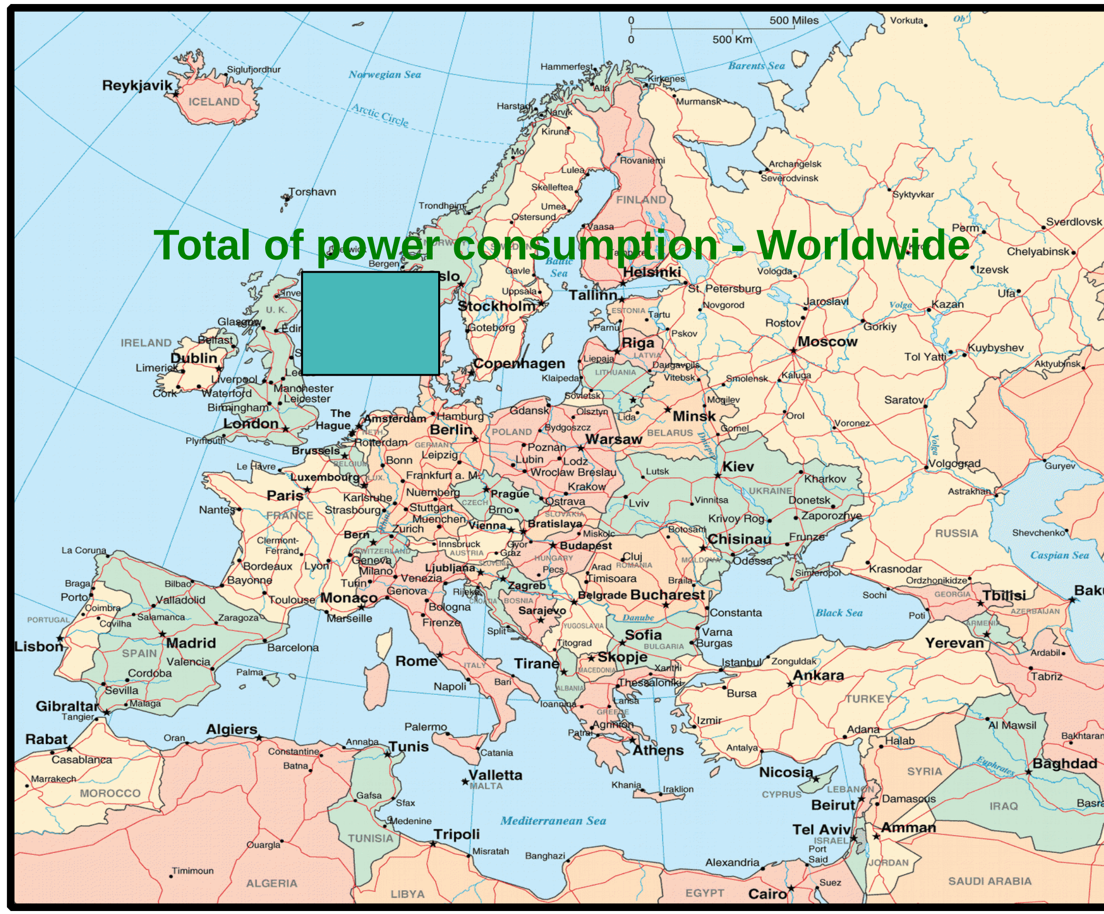
Potentials and Challenges for renewable energy

- **Scenario:** We want to cover the worlds entire need for power using wind power
- How large an area should be covered by wind turbines?
- **Conclusion**: Use data intelligence ....
- Calls for **IT / Big Data / Grey-Box Models for Integration of Renewable Energy**



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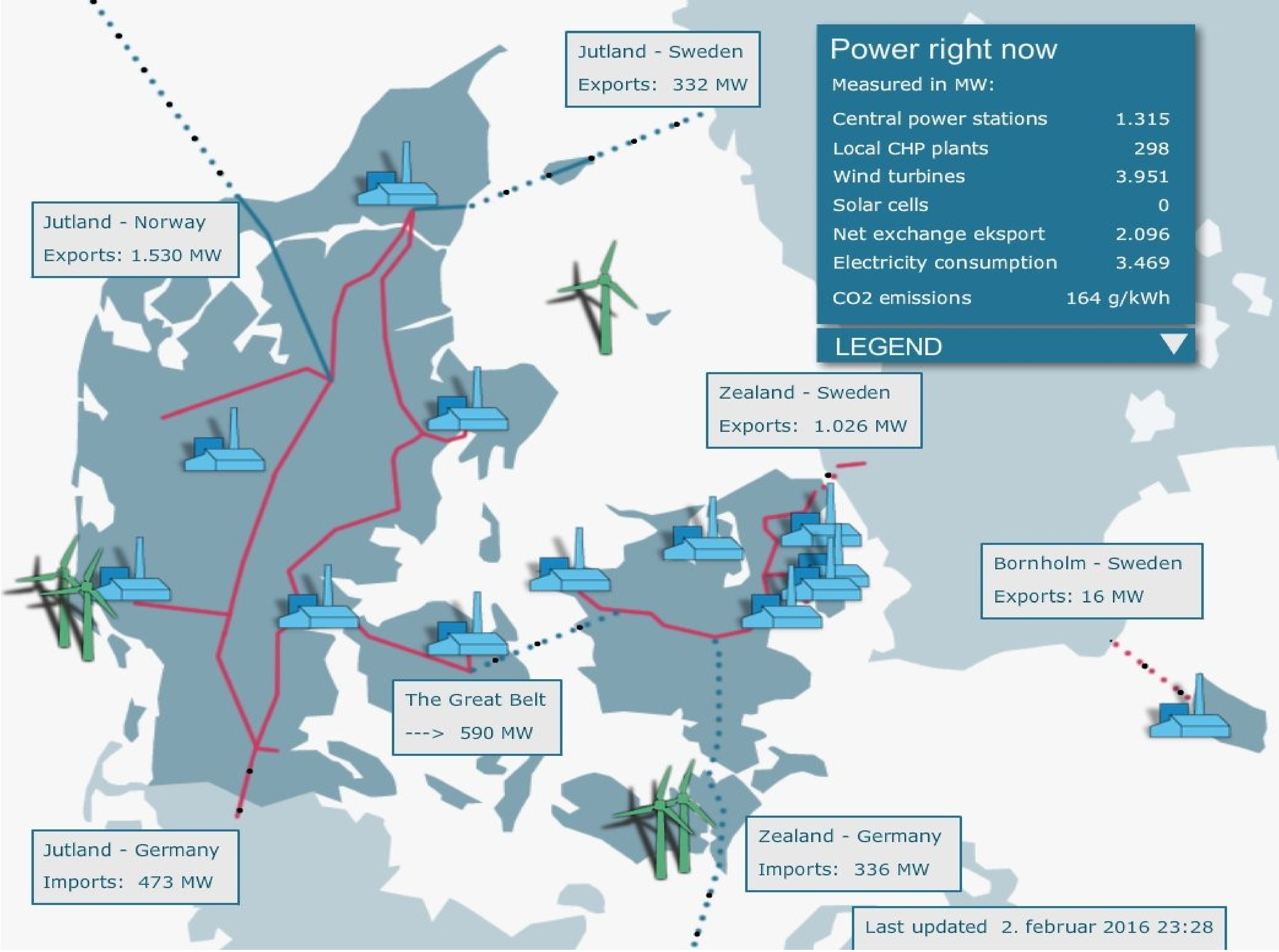

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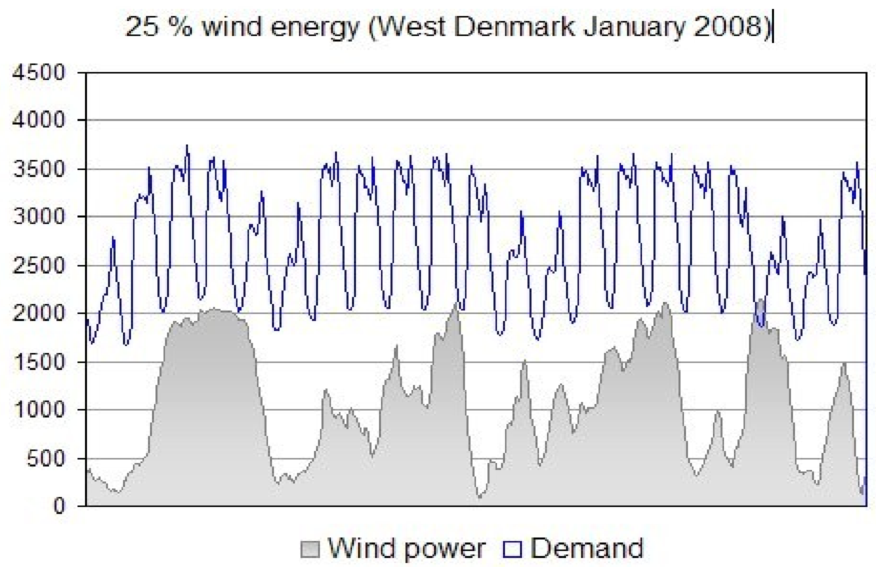
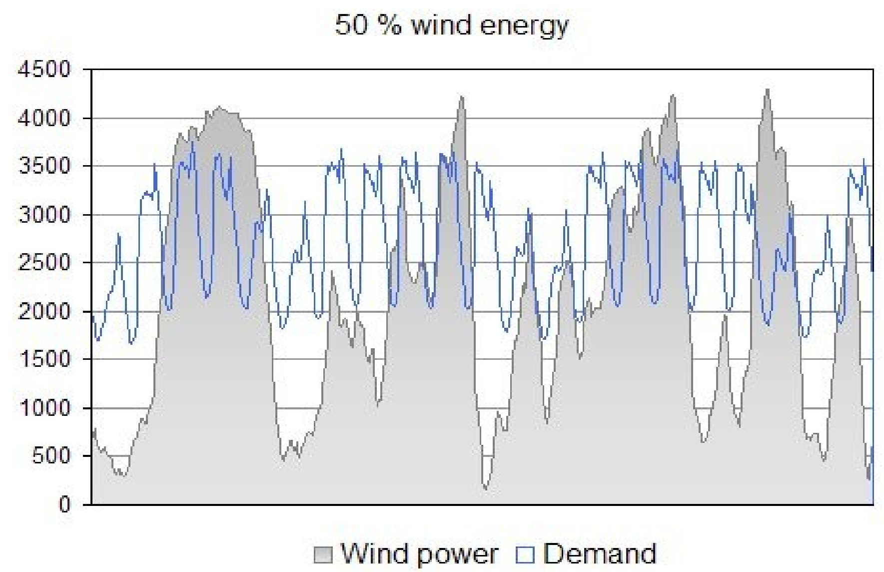
The Danish Wind Power Case

.... balancing of the power system





In 2008 wind power did cover the entire demand of electricity in 200 hours (West DK)

In 2017 more than 44 pct of electricity load was covered by wind power.

For several days the wind power production was more than 100 pct of the power load.

July 10th, 2015 more than 140 pct of the power load was covered by wind power

Challenges

Preparatory study on Smart Appliances

European Commission

Ecodesign Preparatory Study performed for the European Commission

Welcome | **Project summary** | Planning & Meetings | Documents | Register for website | Register for meeting | Contact & Consortium

Home > Project summary

Project Summary

The Ecodesign Preparatory Study on Smart Appliances (Lot 33) has analysed the technical, economic, market an tal aspects with a view to a broad introduction of smart appliances and to develop adequate policy approaches supporting such uptake.

The study deals with Task 1 to 7 of the Methodology for Energy related products (MEErP) as follows:

- Scope, standards and legislation (Task 1, Chapter 1);
- Market analysis (Task 2, Chapter 2);
- User analysis (Task 3, Chapter 3);
- Technical analysis (Task 4, Chapter 4);
- Definition of Base Cases (Task 5, Chapter 5);
- Design options (Task 6, Chapter 6);
- Policy and Scenario analysis (Task 7, Chapter 7).

An executive summary of the project results can be downloaded here.

Throughout the study, new relevant aspects have come up which will be covered in a second phase of the Preparatory Study:

- Chargers for electric cars: technical potential and other relevant issues in the context of demand response.
- The modelling done in the framework of MEErP Task 6 and 7 will be updated with PRIMES data that recently became available, and with the EEA-countries.
- The development and assessment of policy options that were identified in the study will be further elaborated and deepened.

Almost no Flexibility

Data Intelligent Energy Systems for a Smart Society

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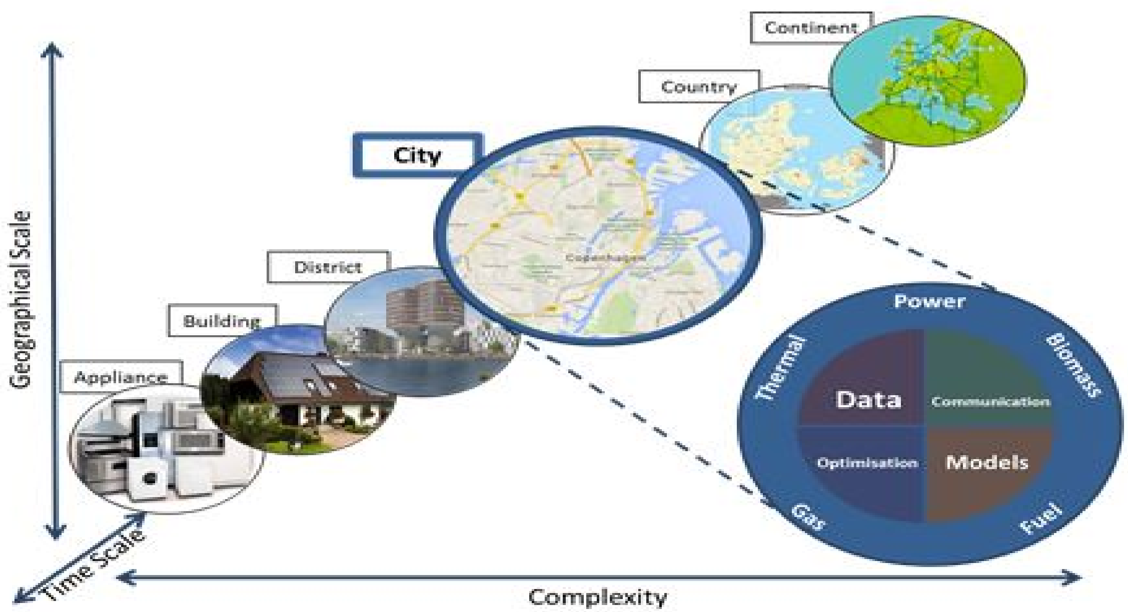
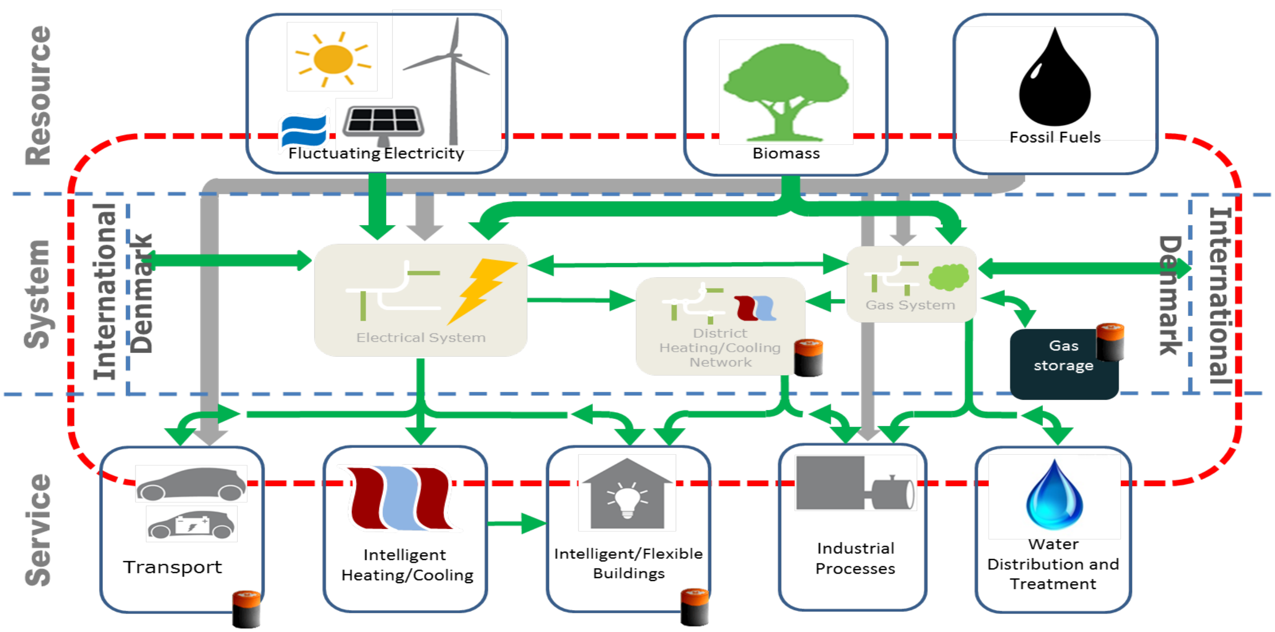
Temporal and Spatial Scales

The ***Smart-Energy Operating-System (SE-OS)*** is used to develop, implement and test of solutions (layers: data, models, optimization, control, communication) for ***operating flexible electrical energy systems*** at **all scales**.

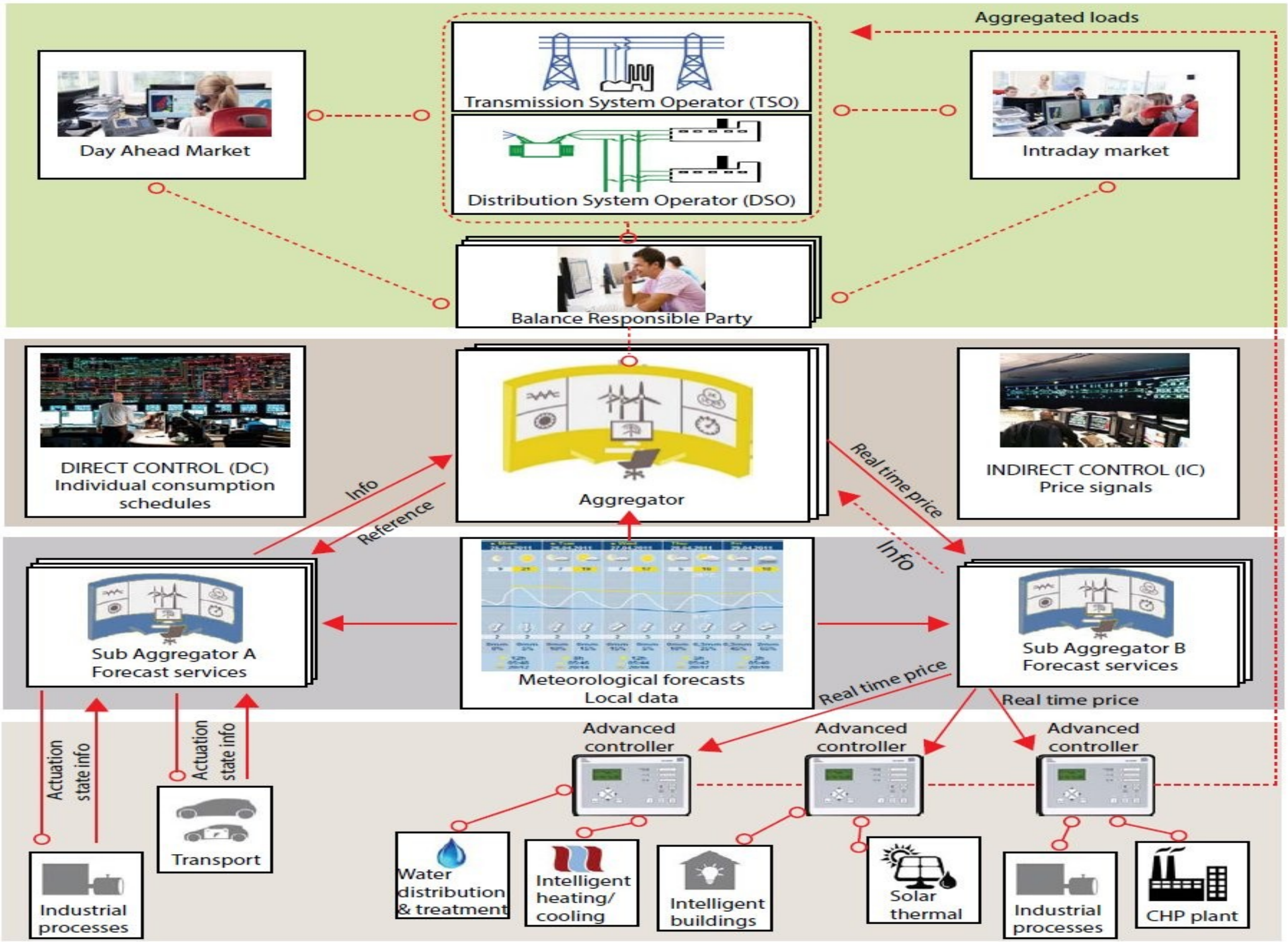


Models for Systems of Systems

Intelligent systems integration using **big data and ICT solutions** are based on **grey-box modelling for real-time operation of flexible energy systems**



Smart-Energy OS



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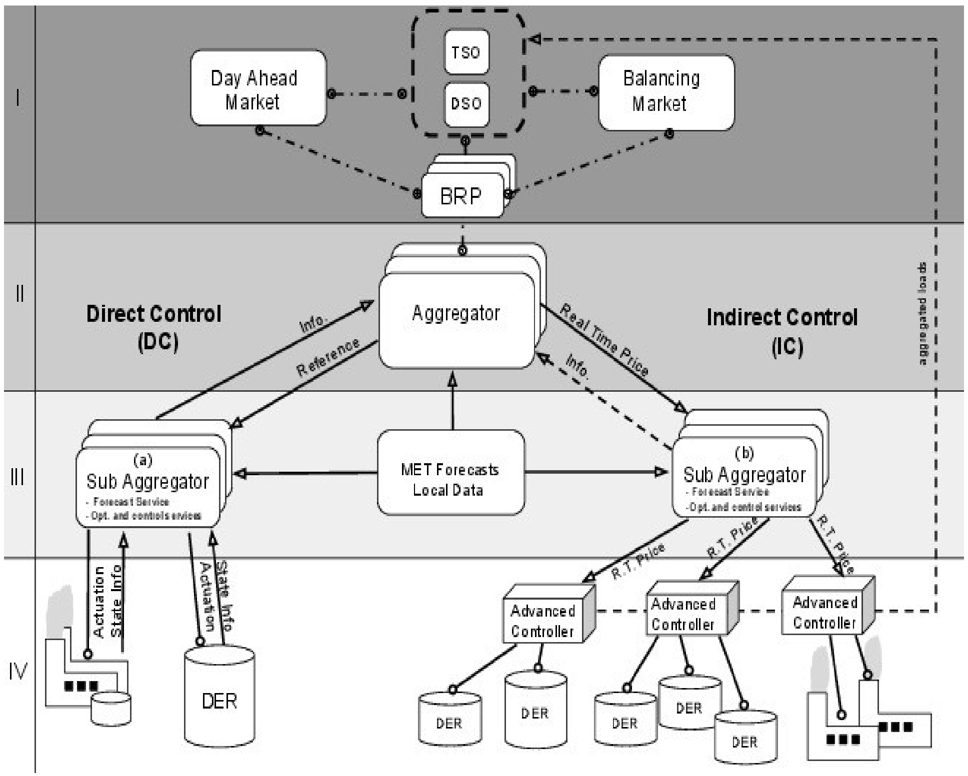
Control and Optimization



In Wiley Book: Control of Electric Loads in Future Electric Energy Systems, 2015

Day Ahead:

Stoch. Programming based on eg. Scenarios

Cost: Related to the market (one or two levels)

Direct Control:

Actuator: **Power**

Two-way communication

Models for DERs are needed

Constraints for the DERs (calls for state est.)

Contracts are complicated

Indirect Control:

Actuator: **Price**

Cost: E-MPC at **low (DER) level**, One-way communication

Models for DERs are not needed

Simple 'contracts'

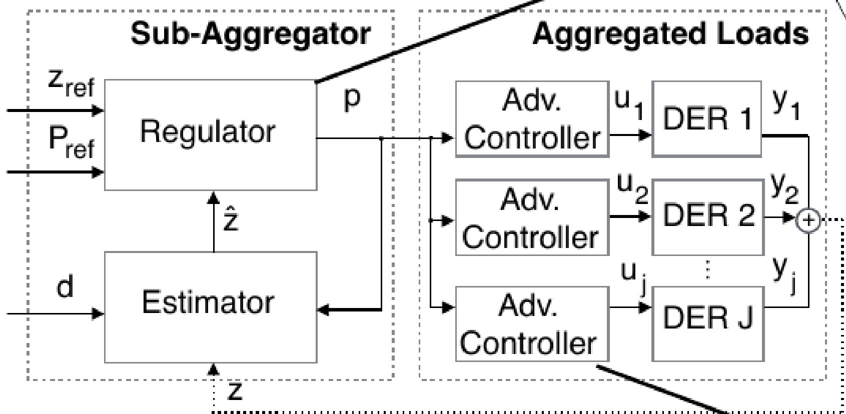
```r
# Slow approach, but we are sure things get do
# Try to parallelize anyway
require(multicore)
numcores<-multicore:::detectCores()
mclapply(
  1:N, 
  function(i,data) {
    print(paste(i, "/", N))

    # Find the indices of rows corresponding to
    j <- which(data$dt_agg %in% aggdata$dt[i])

    # Filter out those who are NA
    j <- j[!is.na(data$last_one_min_power[j])]

    # Count number of readings
    aggdata$num_readings[i] <- length(j)
```

Proposed methodology
Control-based methodology



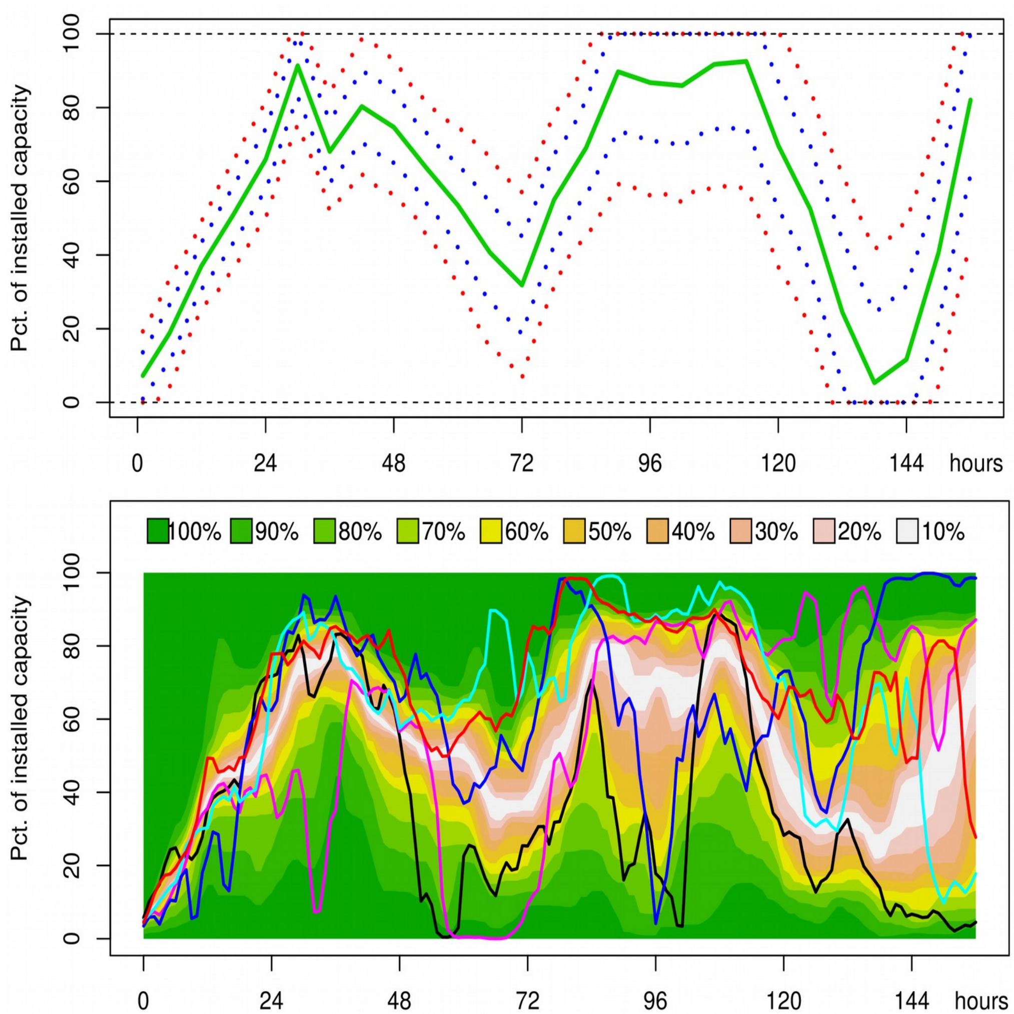
$$
\begin{aligned}
\min_{p} \quad & \mathrm{E}[\sum_{k=0}^{N} w_{j,k}||\hat{z}_k - z_{ref,k}|| + \mu||p_k - p_{ref,k}||] \\
\text{s.t.} \quad & \hat{z}_{k+1} = f(p_k)
\end{aligned}
$$

$$
\begin{aligned}
\min_{u} \quad & \mathrm{E}[\sum_{k=0}^{N}\sum_{j=1}^{J} \phi_j(x_{j,k}, u_{j,k}, p_k)] \\
\text{s.t.} \quad & x_{k+1} = Ax_k + Bu_k + Ed_k, \\
& y_k = Cx_k, \\
& y_k^{min} \le y_k \le y_k^{max}, \\
& u_k^{min} \le u_k \le u_k^{max}
\end{aligned}
$$

We adopt a control-based approach where the **price** becomes the driver to **manipulate** the behaviour of a certain pool flexible prosumers.

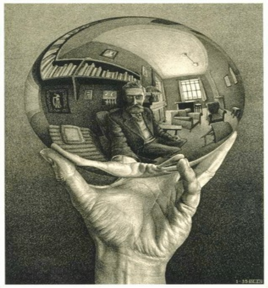
Which type of forecast to use?

- Point forecasts
- Conditional mean and covariances
- Conditional quantiles (Prob. forecasts)
- Conditional scenarios
- Conditional densities
- Stochastic differential equations

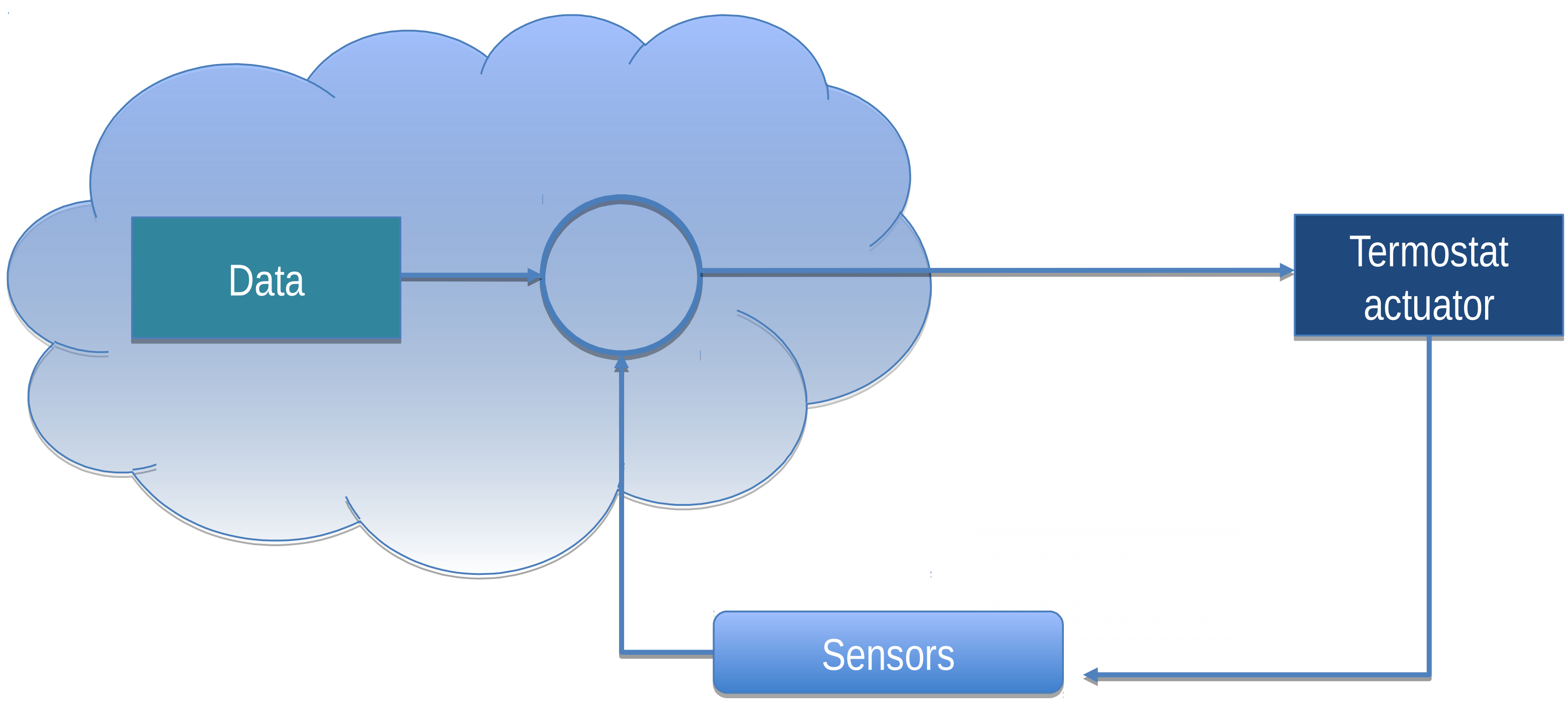


SE-OS Characteristics

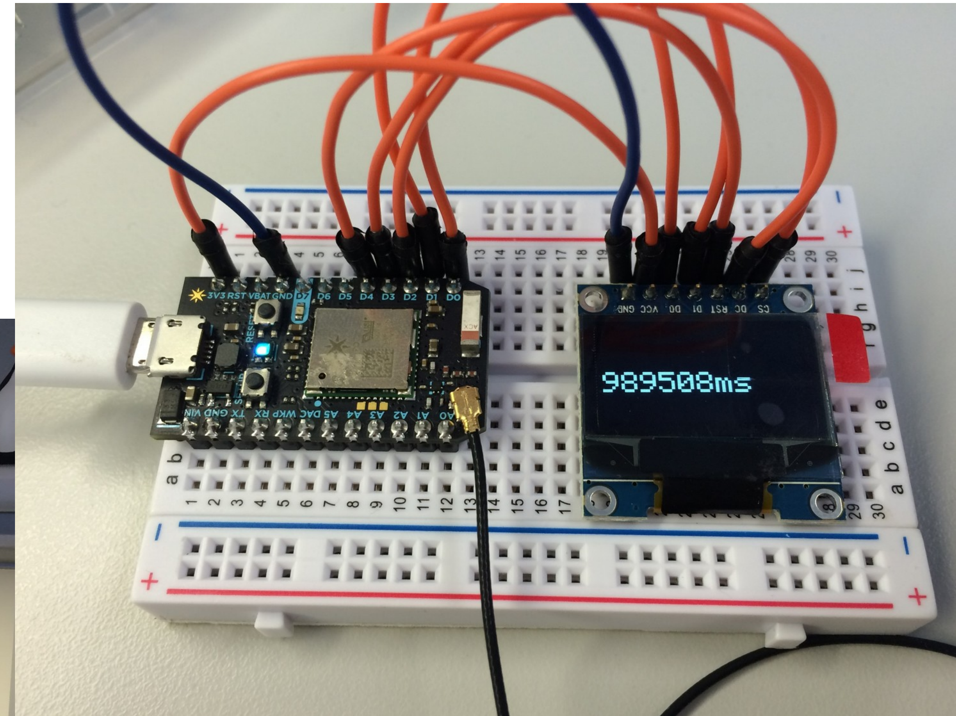
- ‘Bidding – clearing – activation’ at higher levels
- Nested sequence of systems – systems of systems
- Hierarchy of optimization (or control) problems
- Control principles at higher spatial/temporal resolutions
- Cloud or Fog (IoT, IoS) based solutions – eg. for forecasting and control
- Facilitates energy systems integration (power, gas, thermal, ...)
- Allow for new players (specialized aggregators)
- Simple setup for the communication and contracts
- Provides a solution for all ancillary services
- Harvest flexibility at all levels

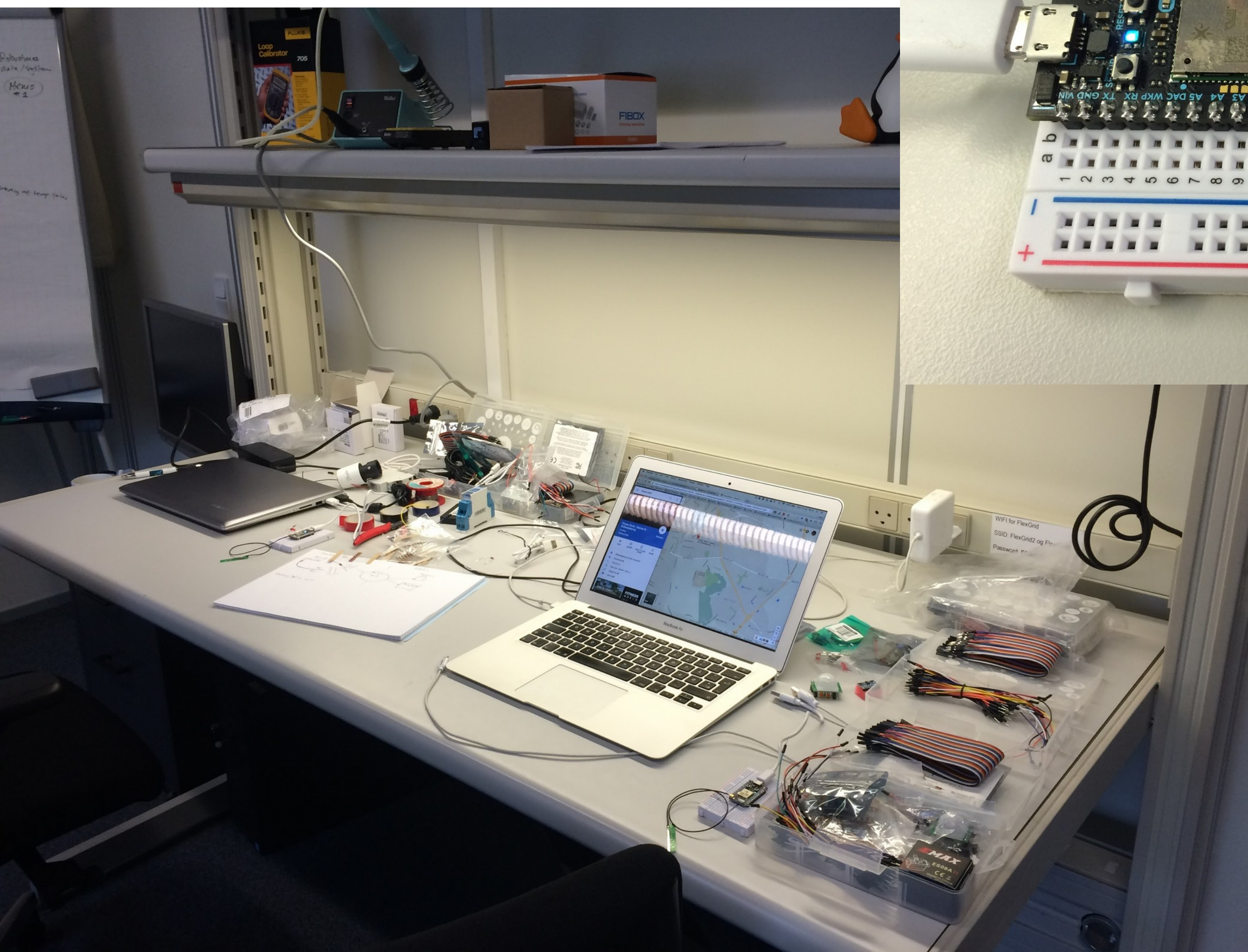


SE-OS
Control loop design – **logical drawing**

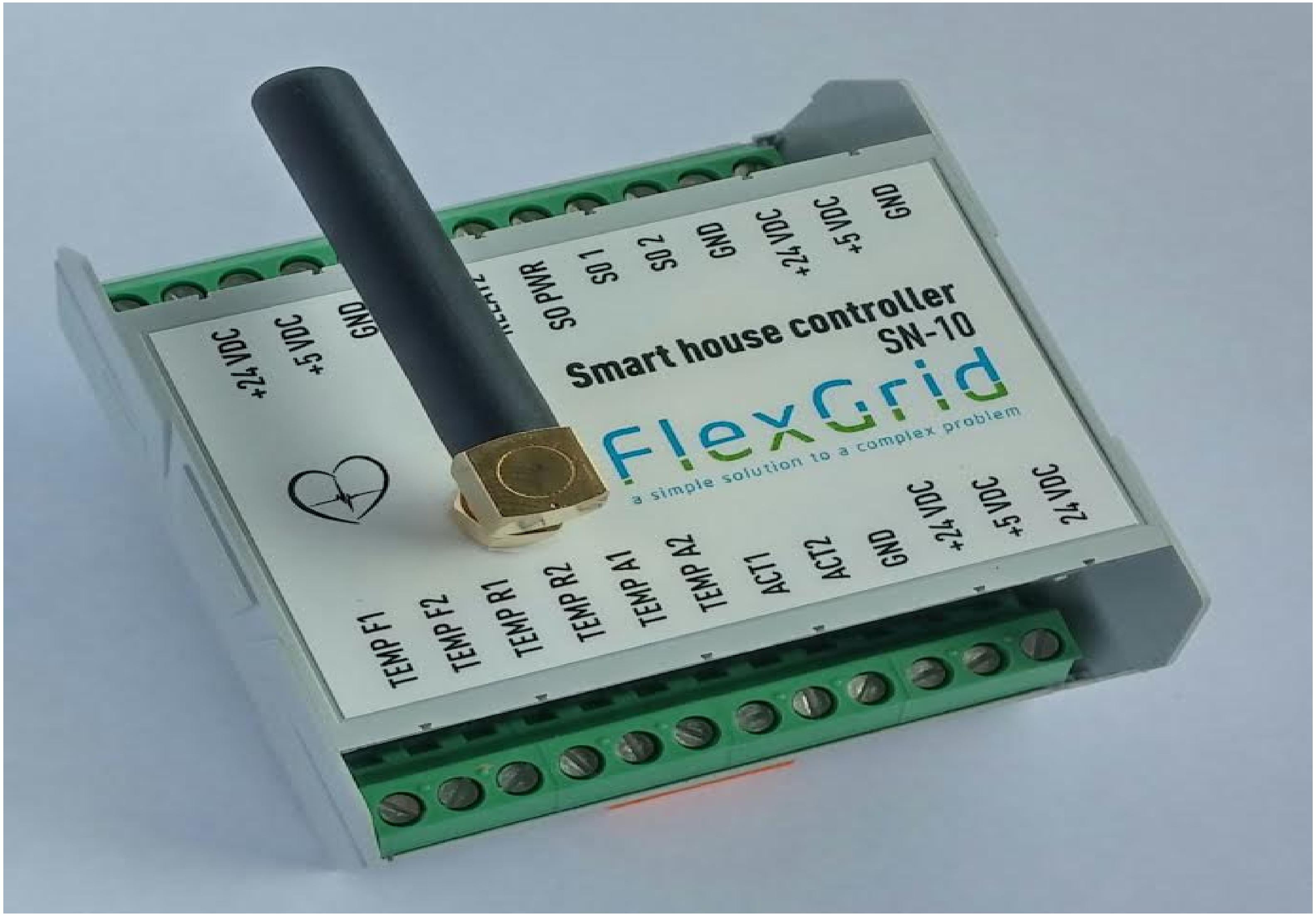


Lab testing ….





SN-10 Smart House Prototype

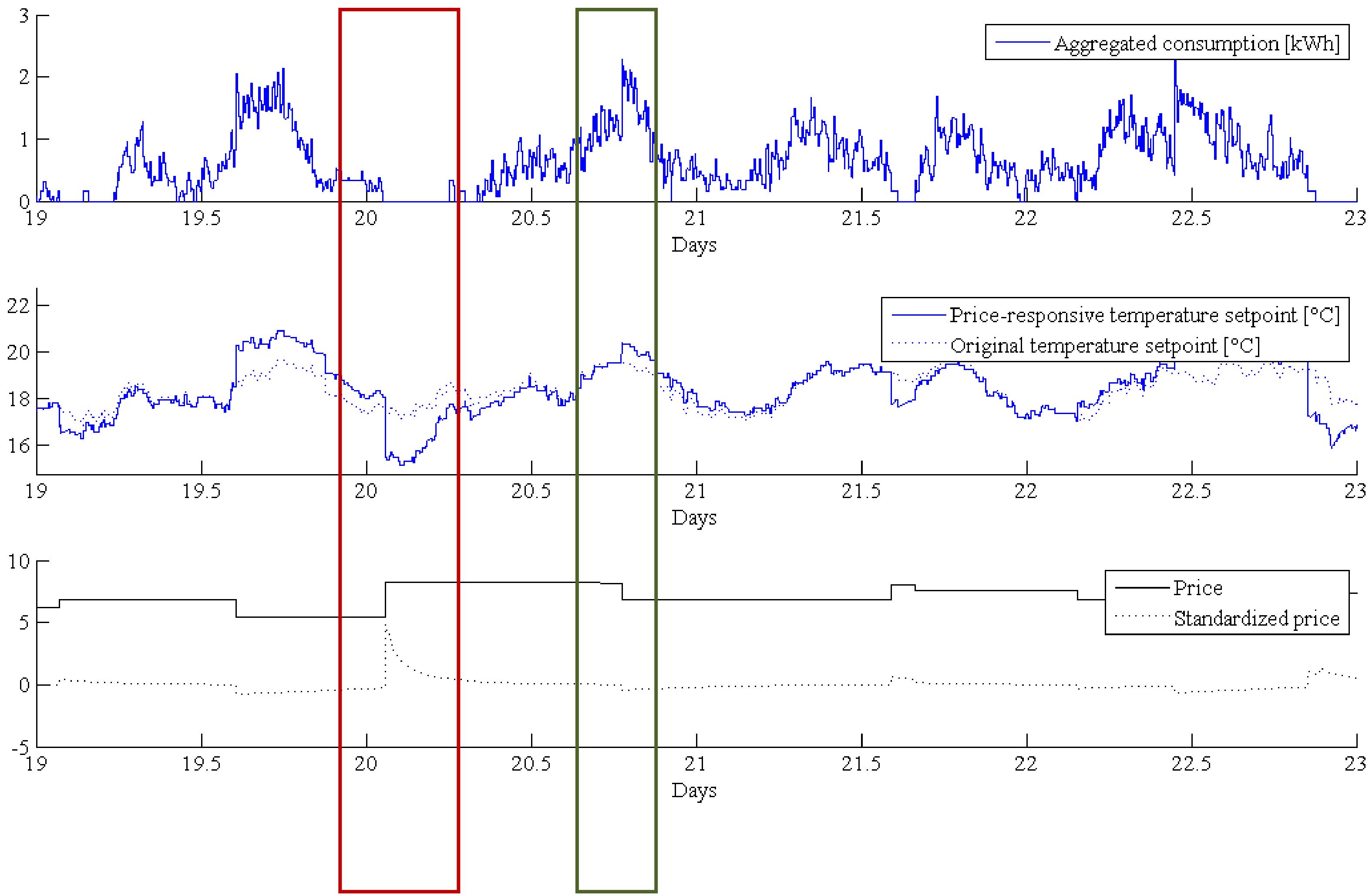


Some case studies ….

Case study No. 1

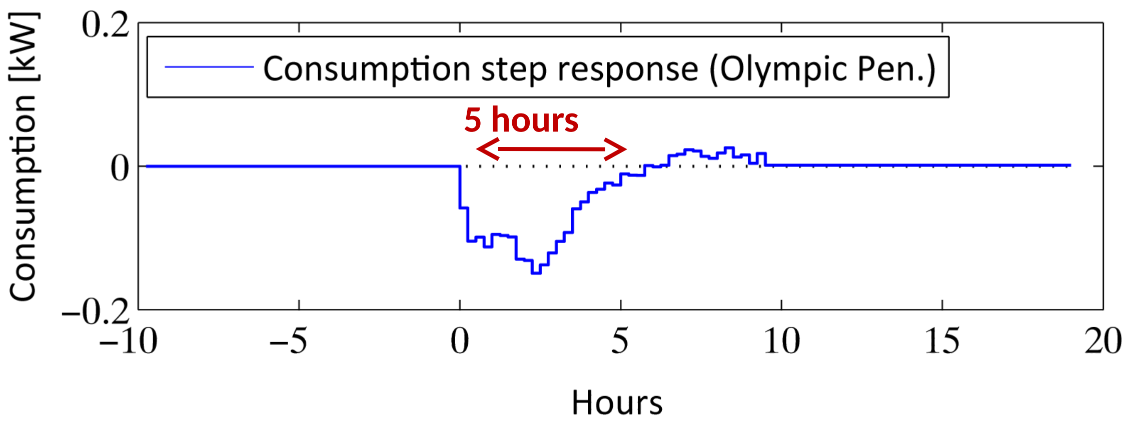
Control of Power Consumption using the Thermal Mass of Buildings (Peak shaving)

Aggregation (over 20 houses)

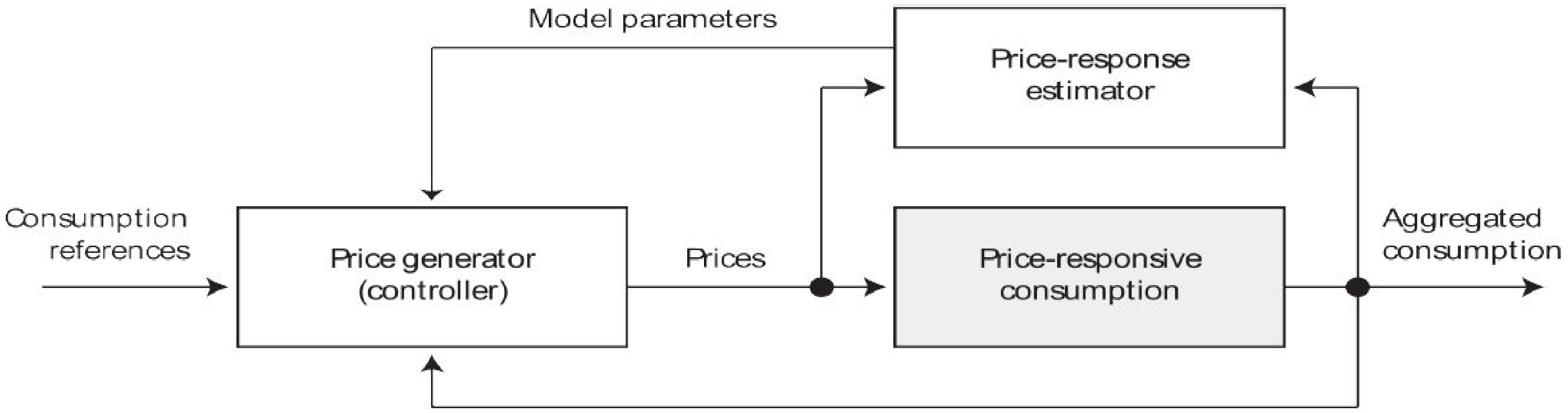


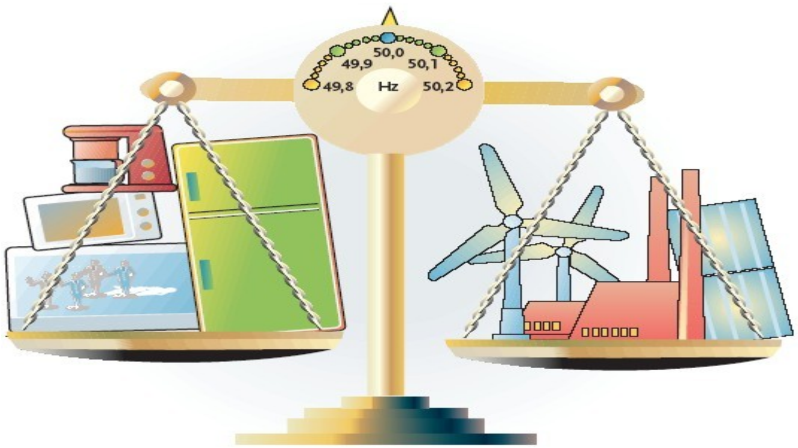
Non-parametric Response on Price Step Change

Olympic Peninsula



Control of Energy Consumption

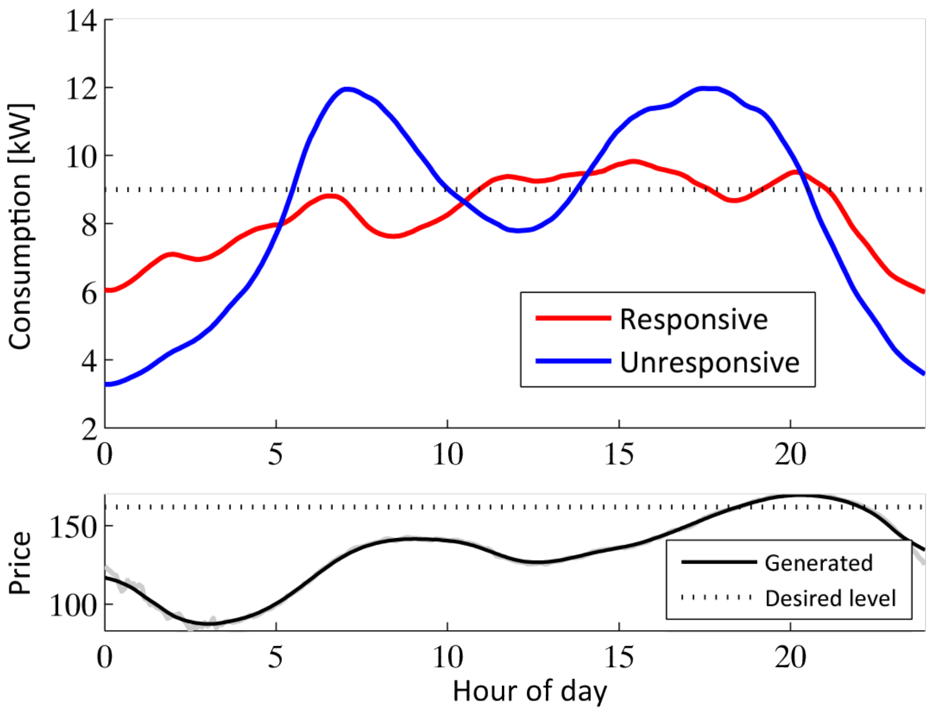




Control performance

Considerable **reduction in peak consumption**

Mean daily consumption shift



Case study No. 2

Control of Heat Pumps for buildings with a thermal solar collector (minimizing cost)

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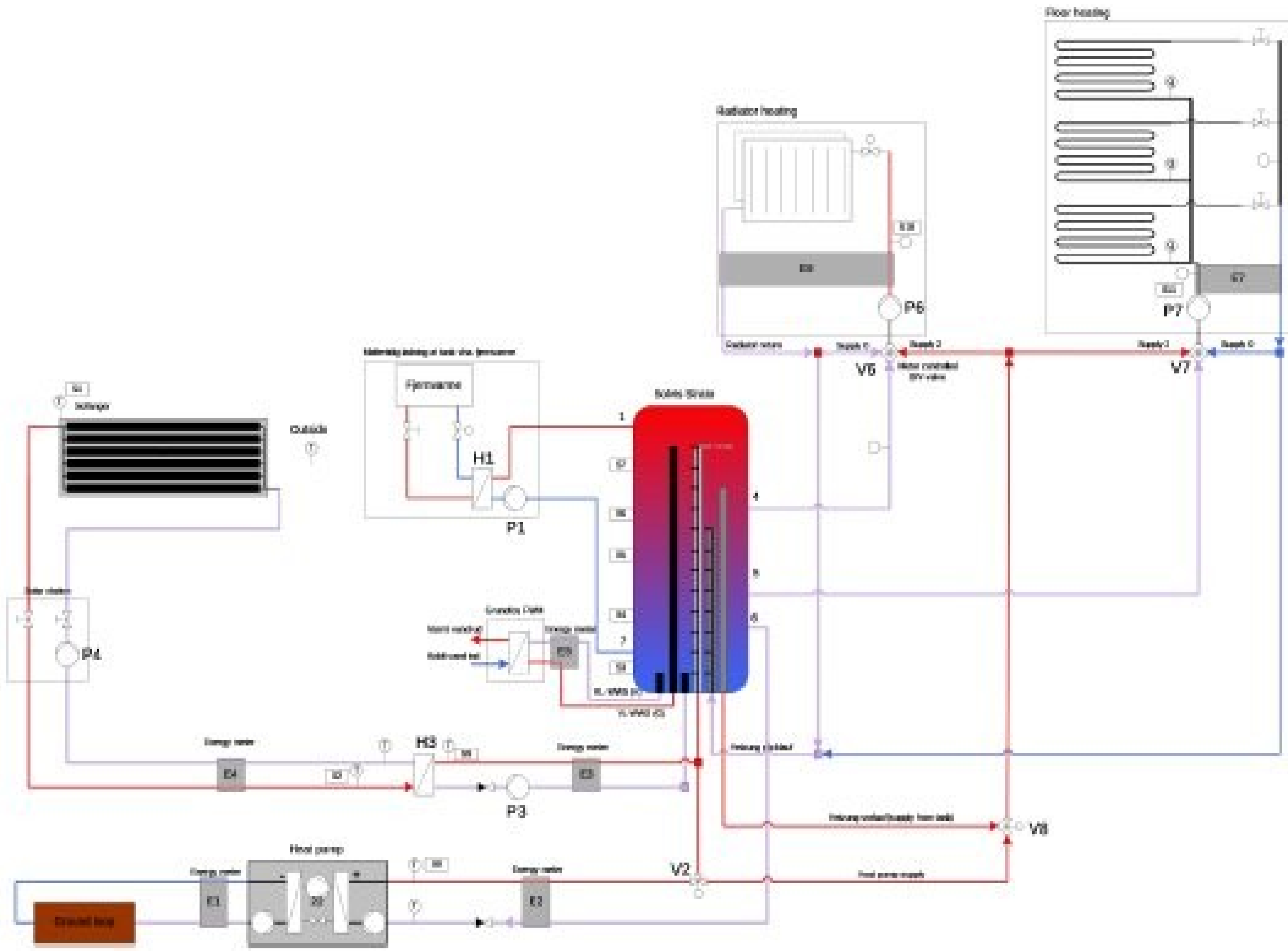
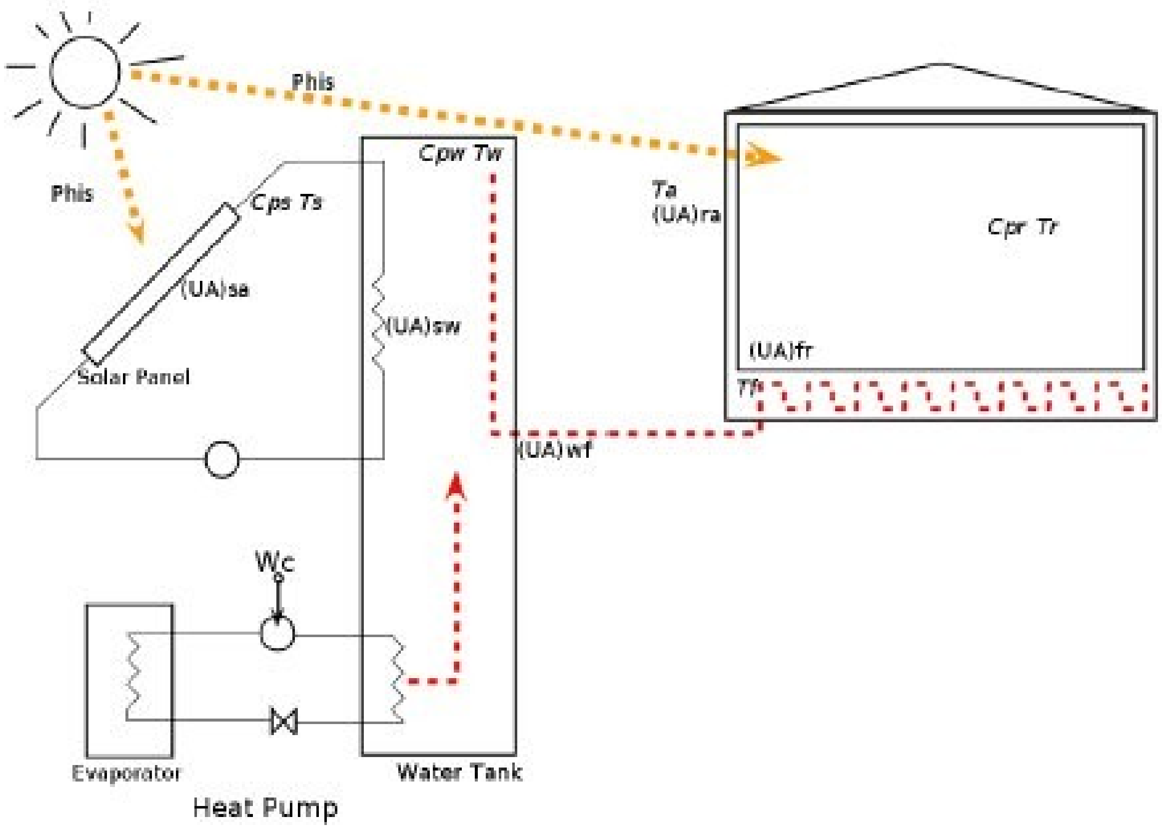
Grundfos Case Study

Schematic of the heating system



Modeling Heat Pump and Solar Collector

Simplified System



Avanced Controller

Economic Model Predictive Control

Formulation

The Economic MPC problem, with the constraints and the model, can be summarized into the following formal formulation:

$$\min_{\{u_k\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} c' u_k \tag{4a}$$

Subject to

$$x_{k+1} = Ax_k + Bu_k + Ed_k \quad k = 0, 1, \ldots, N-1 \tag{4b}$$

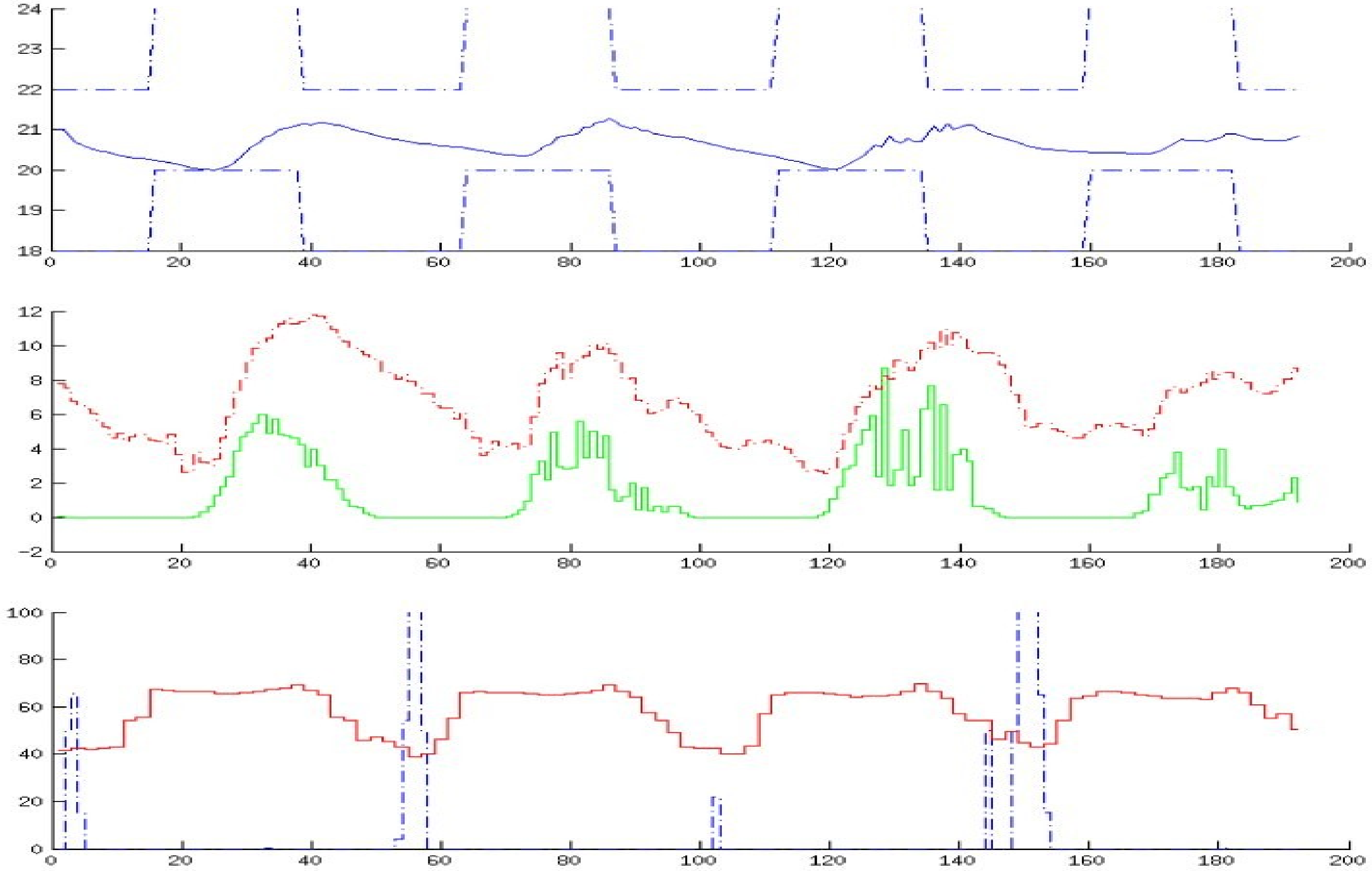
$$y_k = Cx_k \quad k = 1, 2, \ldots, N \tag{4c}$$

$$u_{min} \leq u_k \leq u_{max} \quad k = 0, 1, \ldots, N-1 \tag{4d}$$

$$\Delta u_{min} \leq \Delta u_k \leq \Delta u_{max} \quad k = 0, 1, \ldots, N-1 \tag{4e}$$

$$y_{min} \leq y_k \leq y_{max} \quad k = 0, 1, \ldots, N \tag{4f}$$

EMPC for heat pump with solar collector (savings 30 pct)

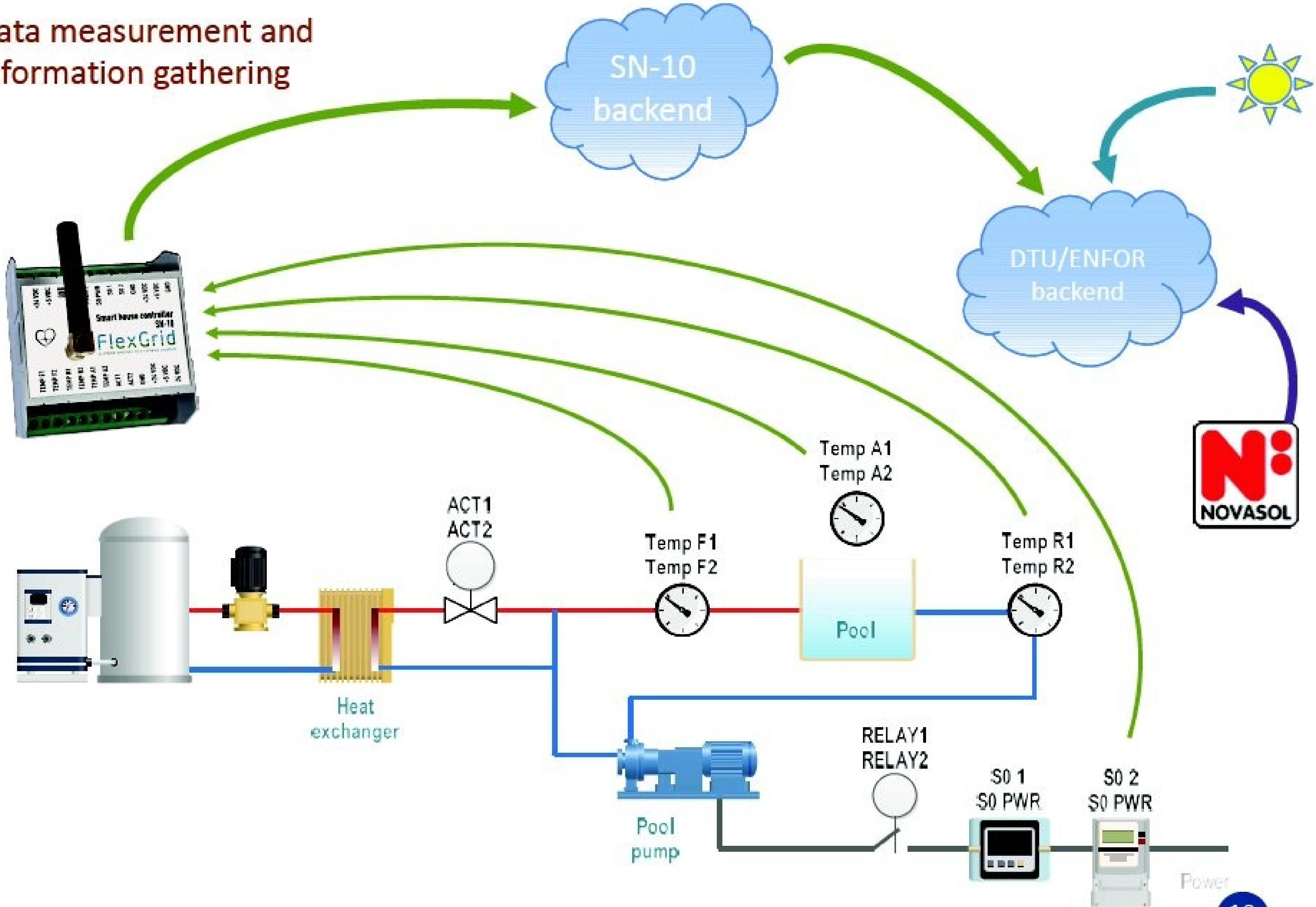


Case study No. 3

Control of heat pumps for swimming pools (Minimization of Cost / CO_2)

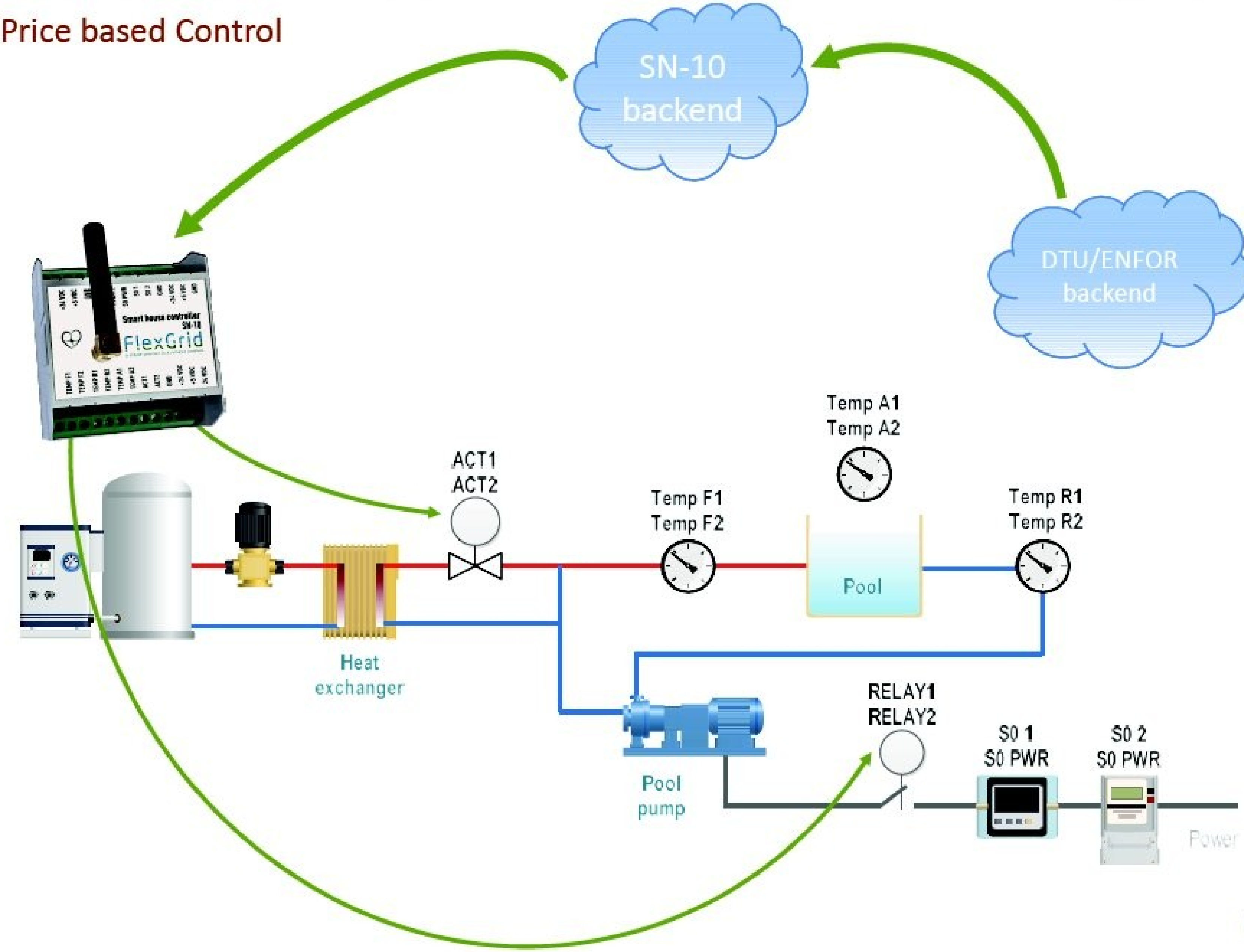
How does it work?

Data measurement and information gathering

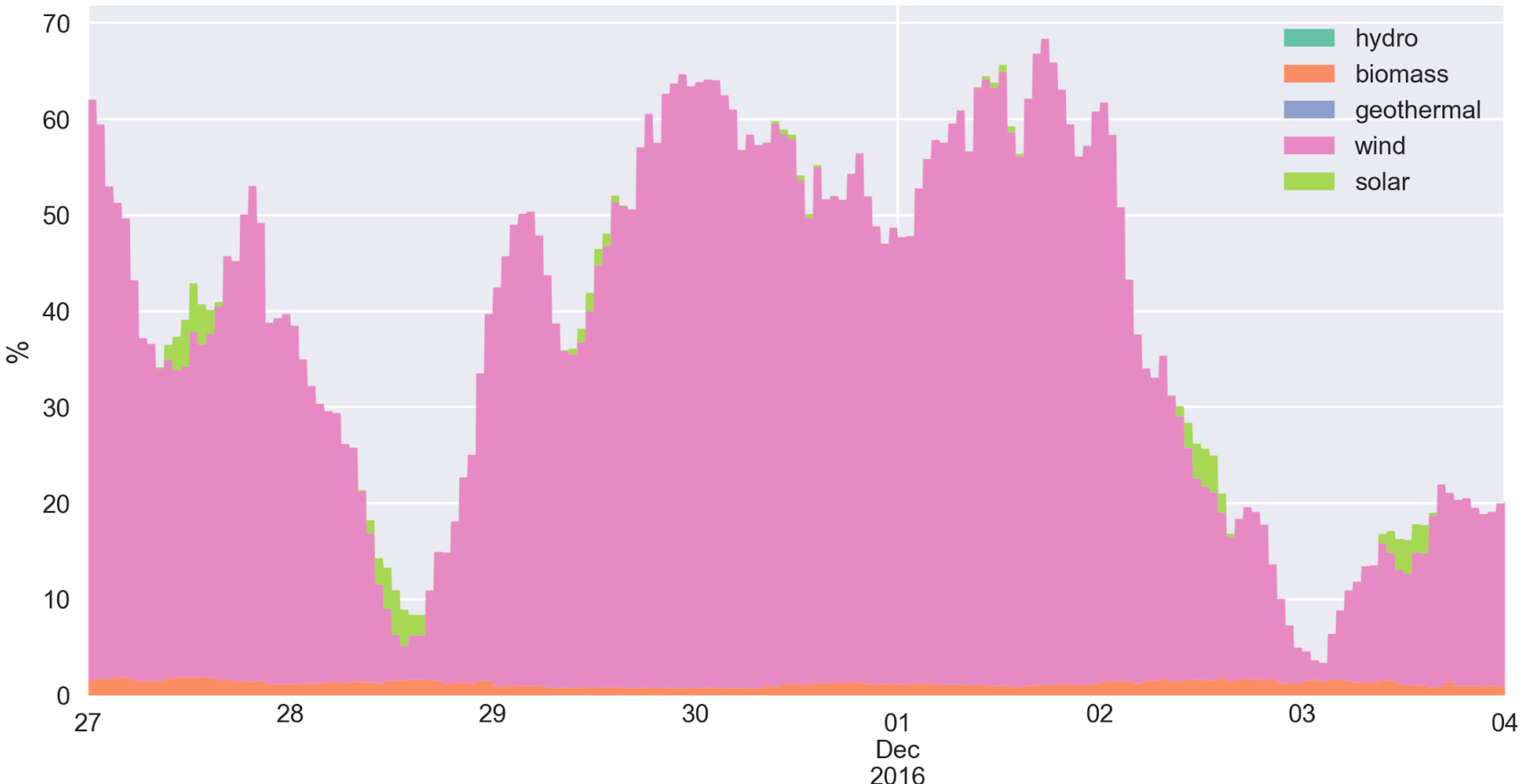


How does it work?

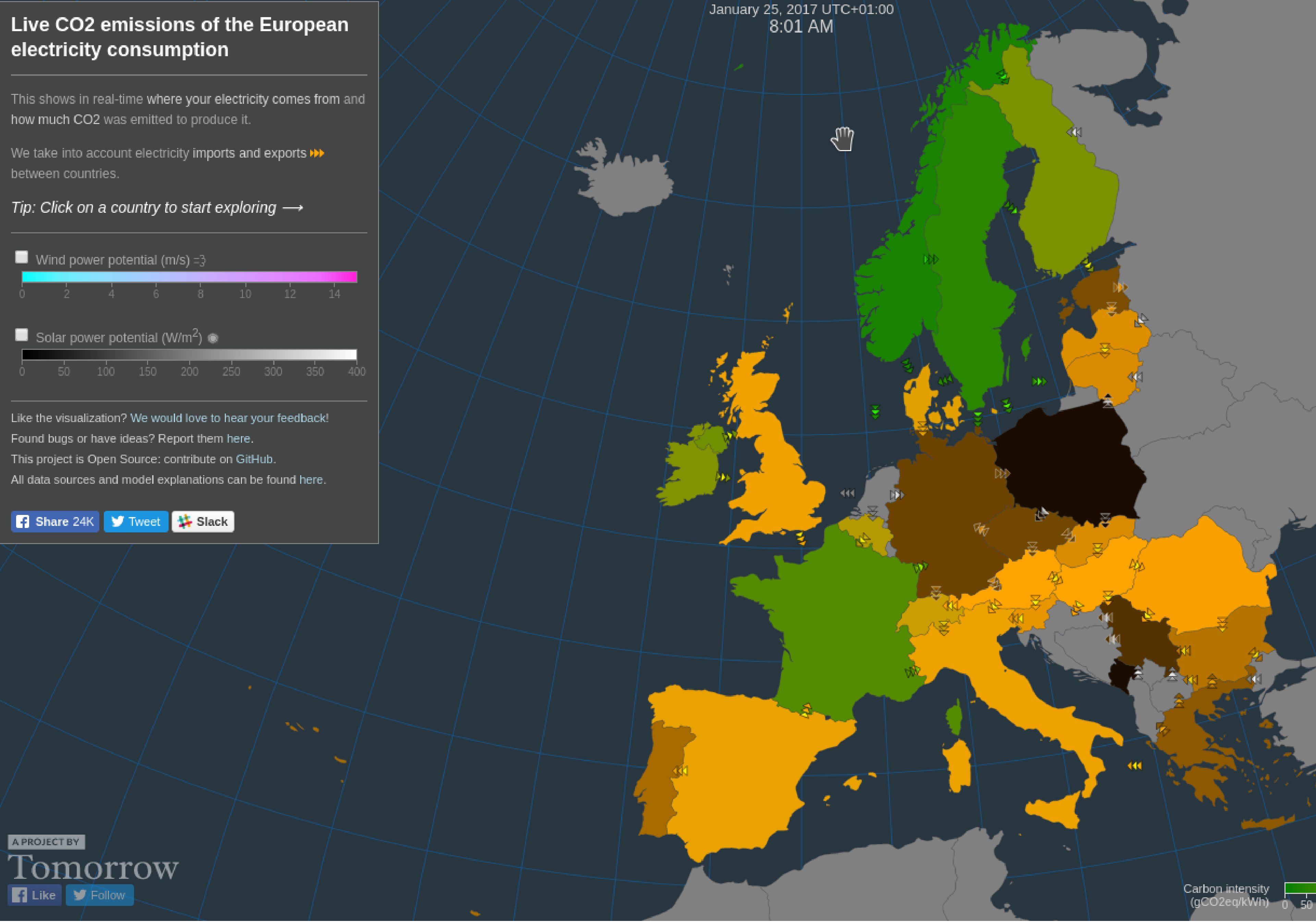
Price based Control



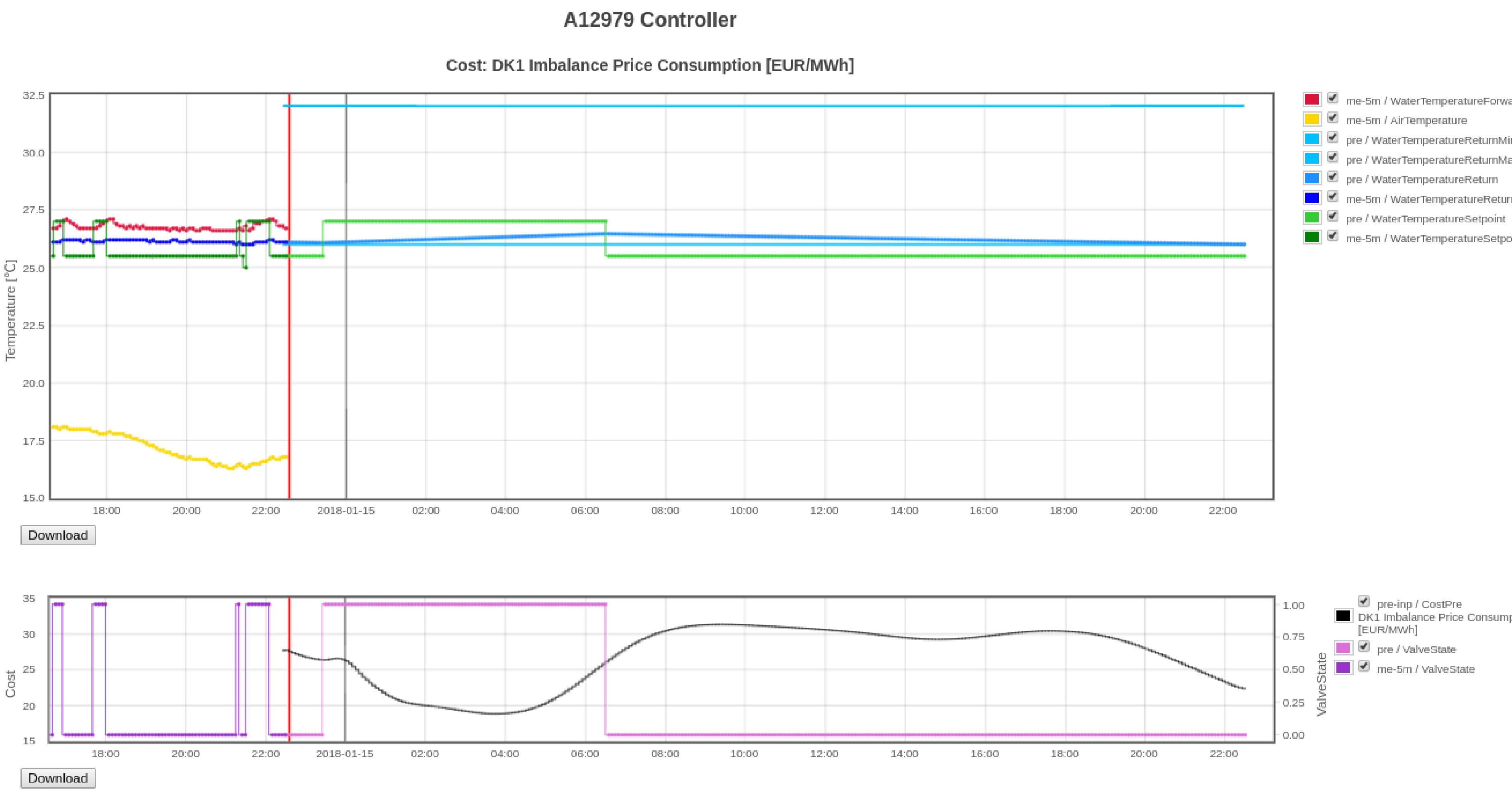
Share of electricity originating from renewables in Denmark Late Nov 2016 - Start Dec 2016



Source: pro.electicitymap.org


Live CO2 emissions of the European electricity consumption
This shows in real-time where your electricity comes from and how much CO2 was emitted to produce it.
We take into account electricity imports and exports between countries.
Tip: Click on a country to start exploring ⟶
Wind power potential (m/s)
0 2 4 6 8 10 12 14
Solar power potential (W/m2)
0 50 100 150 200 250 300 350 400
Like the visualization? We would love to hear your feedback!
Found bugs or have ideas? Report them here.
This project is Open Source: contribute on GitHub.
All data sources and model explanations can be found here.
Share 24K
Tweet
Slack
A PROJECT BY
Tomorrow
Like
Follow
January 25, 2017 UTC+01:00
8:01 AM
Carbon intensity (gCO2eq/kWh)
0 50

Example: Price-based control



Example: CO2-based control

Flexibility Setup and Control

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Characteristics

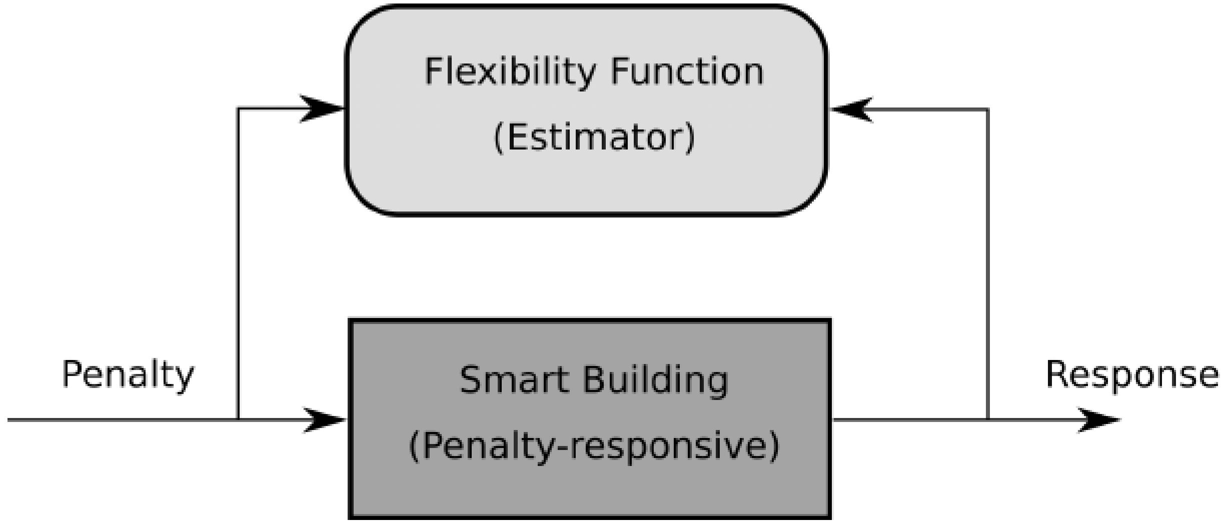


Figure 1: A smart building is able to respond to a penalty or external control signal.

Flexibility Function

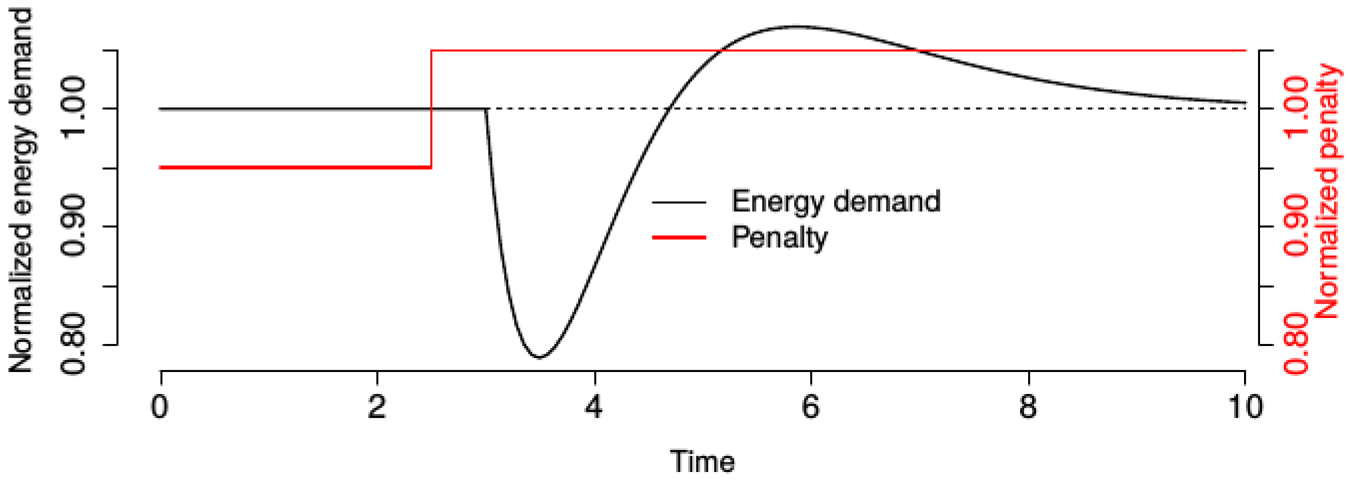


Figure 2: The energy consumption before and after an increase in penalty. The red line shows the normalized penalty while the black line shows the normalized energy consumption. The time scale could be very short with the units being seconds or longer with units of hours. At time 2.5 the penalty is increased,

Equivalent to: Impulse response, transfer function, and frequency response function

FF for three buildings

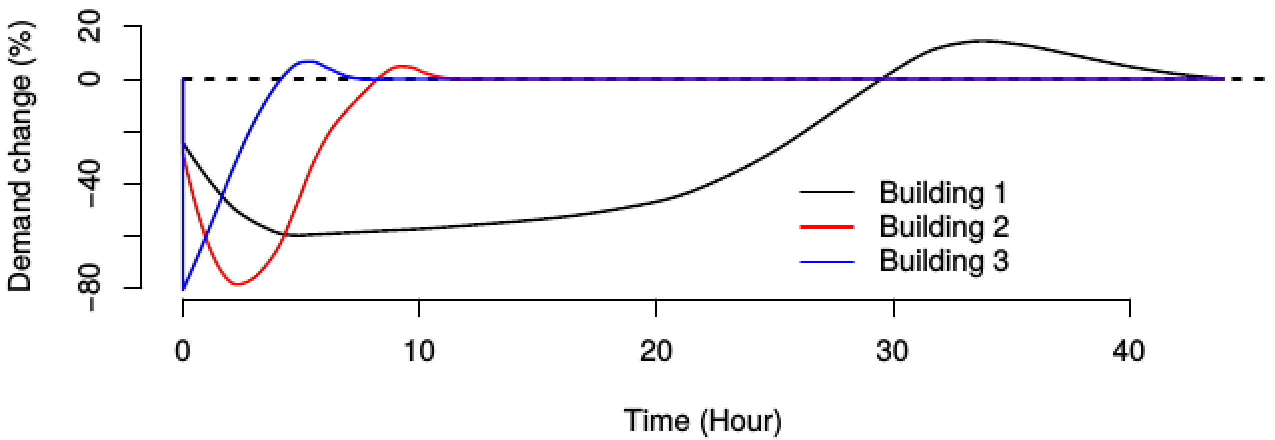


Figure 5: The Flexibility Function for three different buildings.

Penalty Function (examples)

- **Real time CO_2.** If the real time (marginal) CO_2 emission related to the actual electricity production is used as penalty, then, a smart building will minimize the total carbon emission related to the power consumption. Hence, the building will be *emission efficient*.

- **Real time price**. If a real time price is used as penalty, the objective is obviously to minimize the total cost. Hence, the building is *cost efficient*.

- **Constant**. If a constant penalty is used, then, the controllers would simply minimize the total energy consumption. The smart building is, then, *energy efficient*.

Smart Grid Application

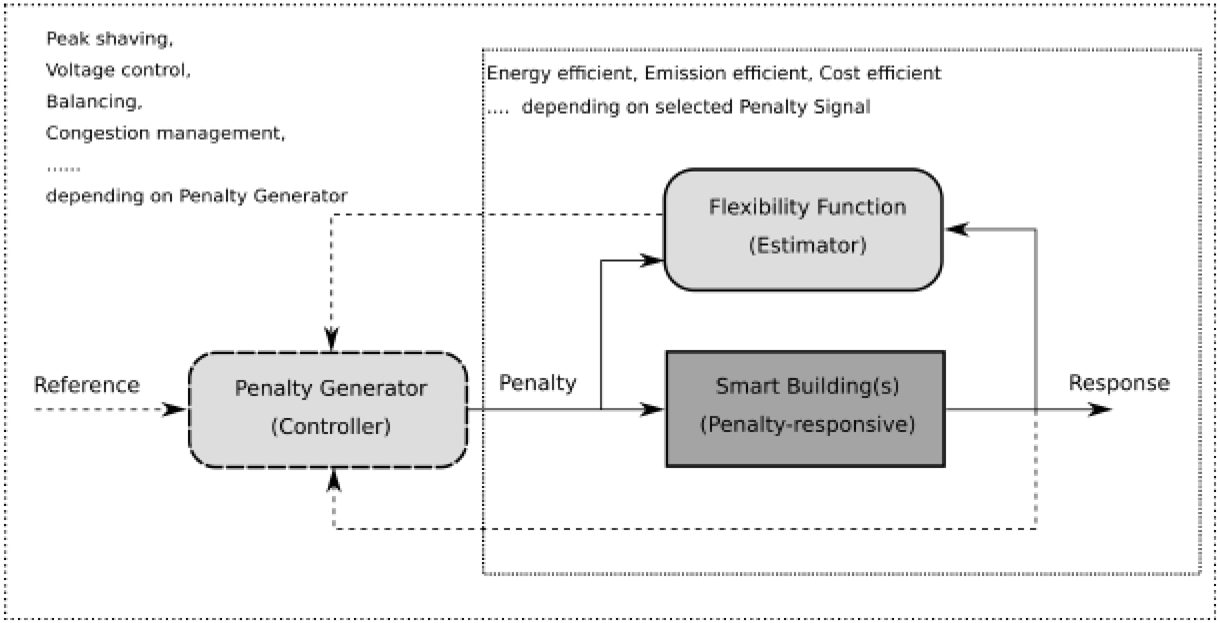


Figure 8: Smart buildings and penalty signals.

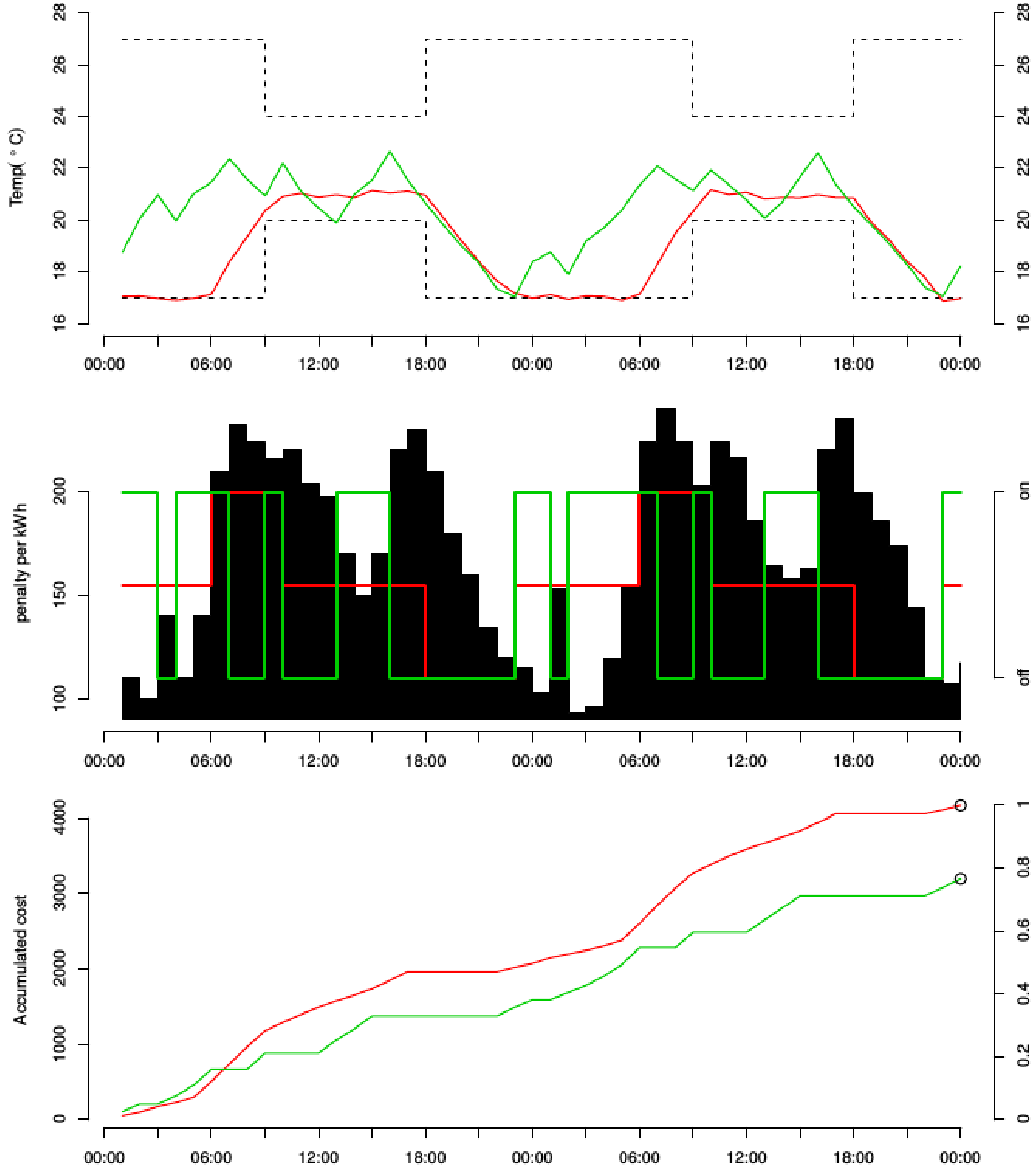
Procedure for calc. Flex. Index

for energy, price and emission based flexibility char.

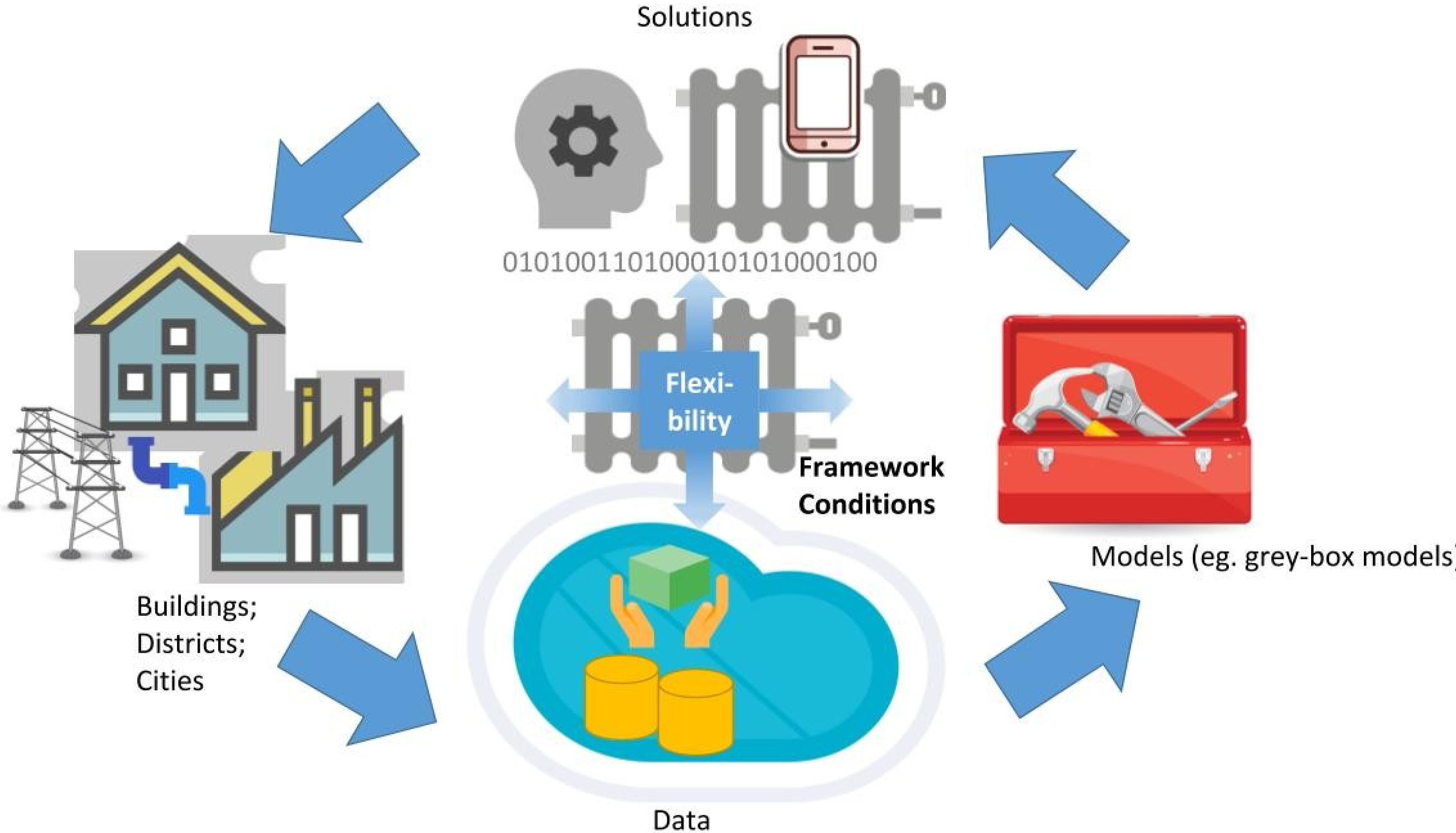
The test consists of the following steps:

1. Let λ_t be the price of electricity at time t.
2. Simulate the control of the building *without considering* the price, and let u_t^0 be the electricity consumption at time t.
3. Simulate the control of the building *considering* the price, and let u_t^1 be the electricity consumption at time t.
4. The total operation cost of the price-ignorant control is given by $C^0 = \sum_{t=0}^{N} \lambda_t u_t^0$.
5. Similarly the operation cost of the price-aware control is given by $C^1 = \sum_{t=0}^{N} \lambda_t u_t^1$.
6. $1 - \frac{C^1}{C^0}$ is the result of the test, giving us the fractional amount of saved money.

This test is inspired by minimizing total costs for varying electricity prices, but in general λ_t could just represent ones desire to reduce electricity demand at time t.


Temp(° C)
16
18
20
22
24
26
28
00:00
06:00
12:00
18:00
00:00
06:00
12:00
18:00
00:00
penalty per kWh
100
150
200
on
off
Accumulated cost
0
1000
2000
3000
4000
0
0.2
0.4
0.6
0.8
1

Flexibility given framework conditions



Realistic Penalties for DK

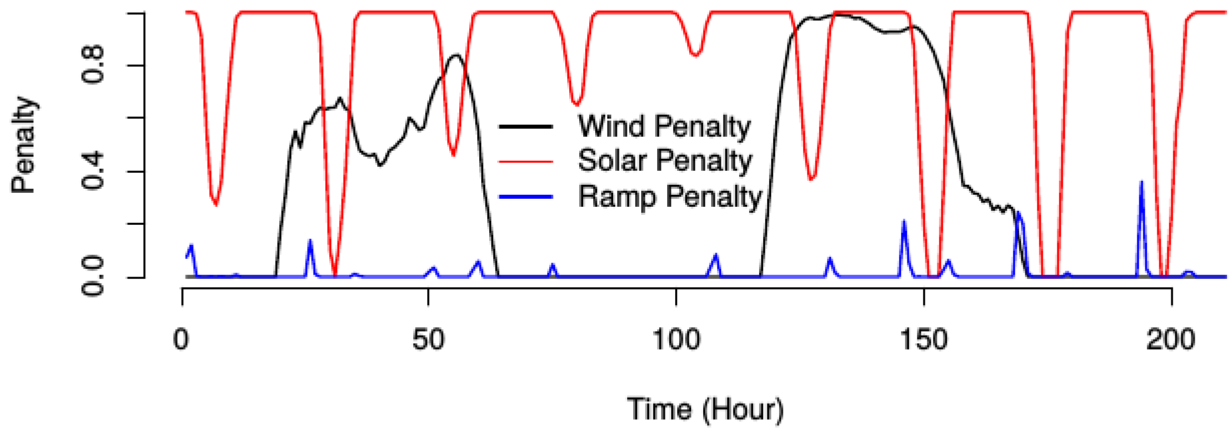


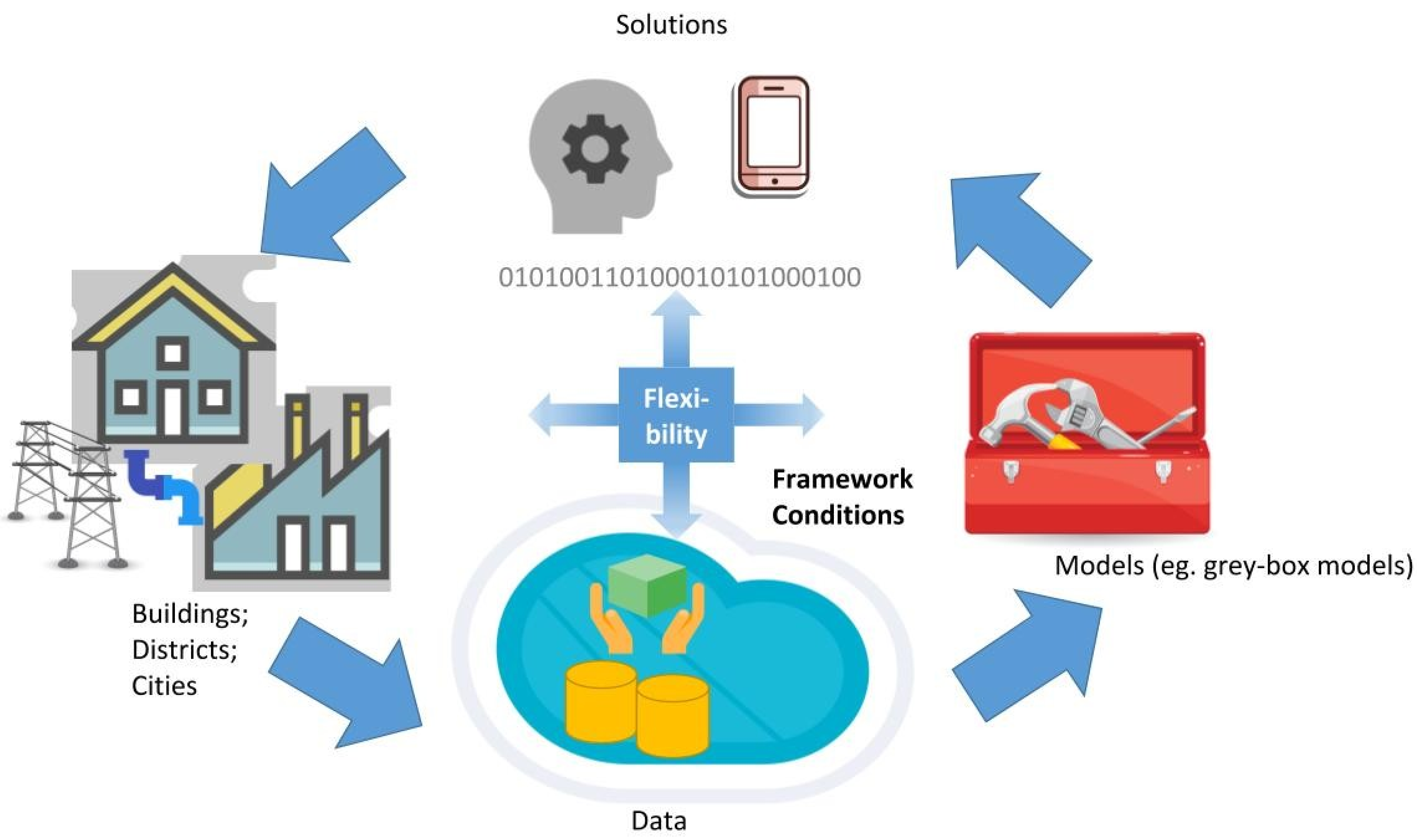
Figure 6: Penalty signals based on wind and solar power production in Denmark during some days in 2017.

Expected Flexibility Savings Index

Table 1: Expected Flexibility Savings Index (EFSI) for each of the buildings based on wind, solar and ramp penalty signals.

	Wind (%)	Solar (%)	Ramp (%)
Building 1	11.8	3.6	1.0
Building 2	4.4	14.5	5.0
Building 3	6.0	10.0	18.4

Flexibility without framework conditions



Reference Penalties

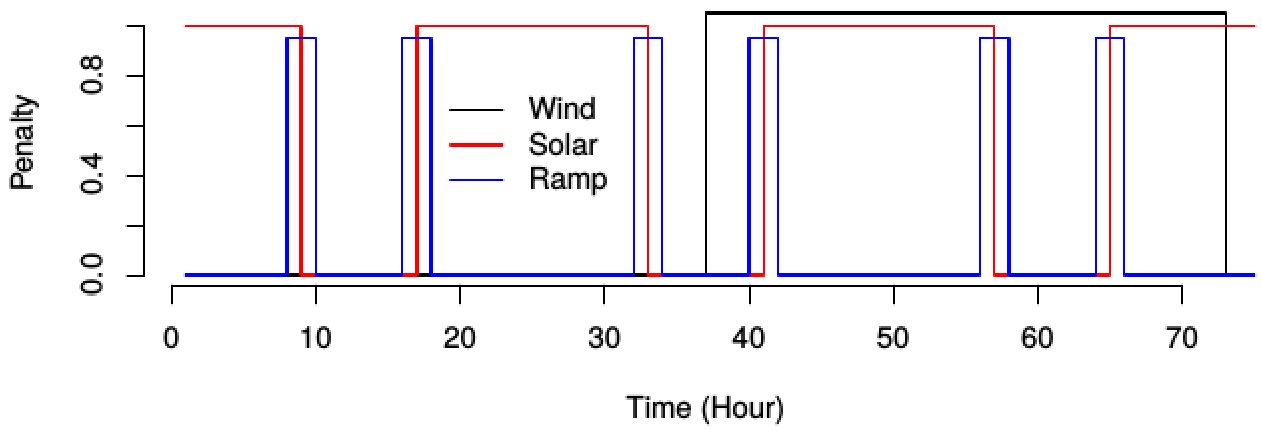


Figure 7: Reference scenarios of penalty signals related to ramping or peak issues as well as the integration of wind and solar power.

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Flexibility Index

Table 2: Flexibility Index for each of the buildings based reference penalty signals representing wind, solar and ramp problems.

	Wind (%)	Solar (%)	Ramp (%)
Building 1	36.9	10.9	5.2
Building 2	7.2	24.0	11.1
Building 3	17.9	35.6	67.5

Summary

- A framework called Smart-Energy OS based on grey-box modelling is described for implementing smart energy systems
- A number of case studies related to smart buildings is outline
- The SE-OS setup can focus on
  - Energy Efficiency
  - Cost Efficiency (Minimization)
  - Emission Efficiency (-> accelerating the transition to a low-carbon energy system)
  - Smart Grid demand (like ancillary services needs, ...)
- We have demonstrated a large potential for unlocking the flexibility and for demand response using grey-box modelling and AI
- We have suggested a method for characterizing the energy flexibility which facilitates smart grid applications and optimizes an integration of fluctuating renewables

For more information ...

See for instance

www.smart-cities-centre.org

...or contact

– Henrik Madsen (DTU Compute)

hmad@dtu.dk

Acknowledgement - DSF 1305-00027B

Some references

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